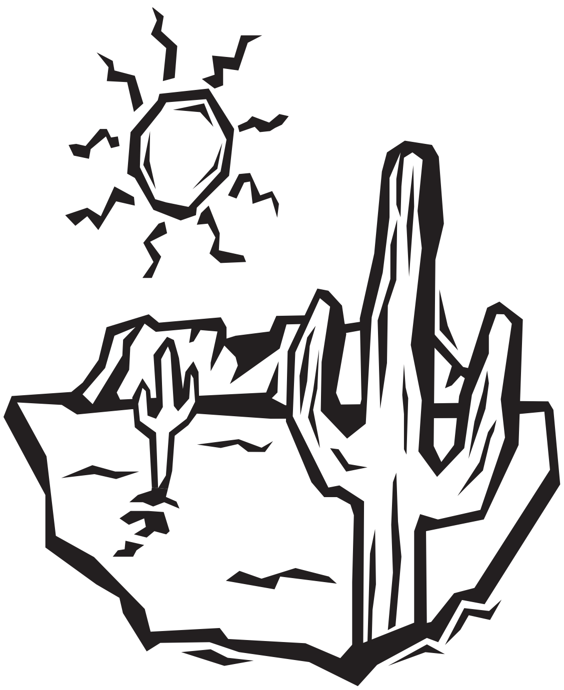
Global Warming in the Southwest

Projections, Observations and Impacts



By Melanie Lenart

With contributions from

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Bonnie Colby
Thomas Swetnam
Barbara J. Morehouse
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CLIMAS Climate Assessment for the Southwest

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Table of Contents

Global warming in the Southwest: An overview

By Melanie Lenart

Global warming will impact different regions and sectors in different ways, creating many losers and even a few winners around the world. Unfortunately, it looks like the Southwest will be on the losing side.

Losing water. Losing cool summer nights. Losing plant and animal species to changing climate patterns. Losing homes, forests, and Sonoran Desert to wildfires.

These are some of the impacts associated with the gains in temperature the Southwest has faced in recent decades–and is projected to continue experiencing for decades to come. The degree of the temperature rise will depend on whether society manages to curb the greenhouse gas emissions spurring on global warming.

The ways global warming and its associated climate changes are likely to affect the Southwest include higher temperatures, with more heat waves; more droughts and, paradoxically, more floods; less snow cover, with more strain on water resources; and an earlier spring with more large wildfires.

Many of these projected and sometimes already observed climate changes have been described in a series of *Southwest Climate Outlook* articles on global warming that ran from December 2003 through this month. The series has been pulled into a compilation, with additional contributions from other University of Arizona (UA) researchers. The book, *Global Warming in the Southwest* (GWS), is available at http://www.ispe.arizona.edu/climas/pubs.html. This article serves as an introduction to the book as well as an update on materials published since the articles were initially written.

The latest research papers and reports generally support the global warming projections, observations, and impacts described in GWS. If anything, they heighten the cause for concern. The case for the Southwest facing extensive drought has gotten stronger. Similarly, more research concludes that the West faces future water shortages because of changing climate. The connection between hot weather and widespread tree die-off has been established more explicitly, as has the link between large wildfires and rising temperatures.

Temperature rise

The warming trend that took hold during the past century, particularly since the mid-1970s, has gotten even more entrenched since the article series started in 2003. The year 2005 went on to surpass 1998 as the world's hottest year in the instrumental record. By the end of 2006, the 10 hottest years on record all had occurred within the past 12 years, based on World Meteorological Association records from 1861.

It's unlikely that every year ahead will continue on this record-setting trend. A large volcanic eruption could cool things down globally for a year or two, as the Mount Pinatubo event in 1991 briefly slowed the temperature rise in the early 1990s. Annual variability could provide temporary relief. Overall, however, temperatures are expected to continue shifting upward throughout the century, as long as society continues to add heat-trapping greenhouse gases to the atmosphere.

The Intergovernmental Panel on Climate Change (IPCC) projects average annual temperature in the Southwest could rise by about 4½ to 7 or more degrees Fahrenheit during this century (*IPCC 2007 Summary for Policymakers*). More details about the IPCC projections, considered the most reliable because they involve the consensus of hundreds of scientists, will be released in May.

Arizona and New Mexico's average annual temperatures could both rise by 7 degrees Fahrenheit throughout this century, based on another projection that applies information from 18 global climate models to the climate division scale (*Southwest Hydrology*, January/February 2007). That amounts to roughly 1 degree Fahrenheit every 14 years. Summer temperatures could rise even more than winter temperatures by these projections, making parts of the Southwest even more intolerable between monsoon rains (see GWS, page 7).

A 1-degree Fahrenheit rise every 14 years may sound dramatic considering it took a whole century for the world's average annual temperature to rise by 1 degree. But this projected rate of increase is actually slightly slower than the rise Arizona experienced since the mid-1970s, and only slightly higher than the increase New Mexico registered in that time frame (Figure 1). These observed values include warming from the urban heat island effect as cities expand.

The number of extremely hot days is also projected to rise over the decades, leaving parts of the region with heat waves lasting an extra two weeks by the end of the century (*Proceedings of the National Academy of Sciences*, November 1, 2005). Hot summers boost the demand for water and electrical cooling (see GWS, page 69). Even worse, heat waves can create health risks, especially among the frail elderly and young children living in inner cities (*Environmental Health Perspectives*, May 2001).

Drought

Drought has further extended its grip on the Southwest in recent years, despite occasional excursions into times of plentiful precipitation, such as the winter of 2004–2005 and the summer of 2006. The latest projections for Southwest precipitation offer no relief in sight.

continued on page 3

GW overview, continued

The Dust Bowl years of the 1930s could become the new norm, based on results from 19 global climate models considered by Columbia University researcher Richard Seager and colleagues (*Science Express*, April 5, 2007). The projections suggest that the Southwest's immediate future would look much like the peak years of 2000–2003 in the Southwest's current drought. Things would only get worse in time, by this projection.

The IPCC also projects dry areas will get drier—in the Southwest and throughout the subtropics (*IPCC Summary for Policymakers*, 2007). This is a reversal of earlier projections in the 2001 IPCC summary that the Southwest might receive more rainfall as climate warms.

The mechanism behind the updated projection relates to a global atmospheric pattern known as Hadley Cell circulation (Figure 2). Globally, rising hot air from the tropics eventually descends in the subtropics. The high pressure of the descending air makes it difficult for clouds to form. This helps explain the seemingly endless supply of sunny days found in subtropical regions like the northern Africa, southern Australia and, of course, the U.S. Southwest.

The area under the Hadley Cell's descending air is projected to widen in years to come. As a result, the jet stream that transports rain and snow during winter and spring is expected to move poleward. In theory, the poleward pattern could mean El Niño events might often fail to bring hoped-for rain and snow to the Southwest. In practice, that pattern might look a lot like this past winter, when Denver received record snowfall while Arizona's dry winter pushed much of the state back into drought. This projection adds another element to the debate over the future of El Niño, one that was not addressed in the original article on page 17 of GWS.

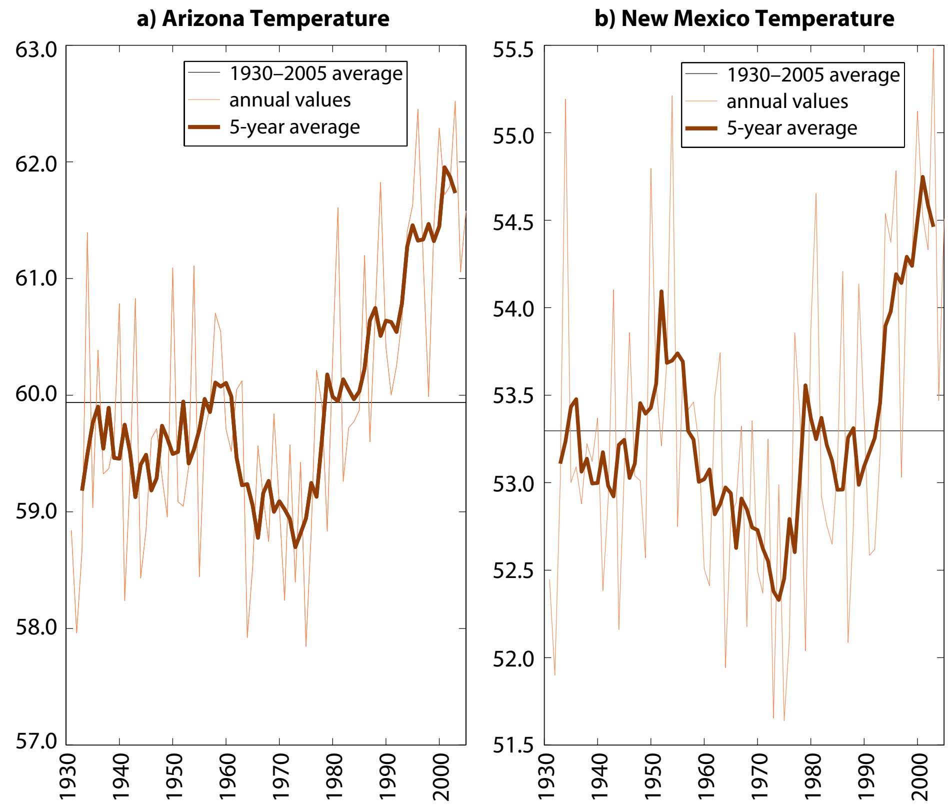

Figure 1. Southwest temperatures have been rising, above. Since 1976, the average annual temperature increased by 2.5 degrees Fahrenheit in Arizona a) and 1.8 degrees Fahrenheit in New Mexico b), or 0.8 degrees and 0.6 degrees Fahrenheit a decade, respectively. Data was averaged from the respective states' climate divisions by Ben Crawford, CLIMAS.

Floods

A more northerly jet stream in summer theoretically might make it easier for the monsoon to reach the Southwest, on the other hand. The jet stream can present a barrier to the monsoon's northward progression from its origin in tropical Mexico (see the two chapters starting on page 20 of GWS).

The monsoon operates at a scale smaller than that modeled by global climate models, making its future difficult to predict. No trend toward increased rainfall during the Southwest's monsoon season shows up in records for 1950–2001, but there are a few reasons to suspect the monsoonal rainfall tallies could increase as land and sea temperatures rise (see GWS, page 20). The projected shift in the jet stream could strengthen that case. A strong monsoon can increase the potential for flooding during this annual summer event. However, even a strong monsoon generally does little to break long-term drought in the Southwest.

The stronger hydrological cycle that comes with global warming can produce seemingly paradoxical effects, including more drought and more floods. Southwestern springs, for instance, have been featuring both heavier rains and drier soils, based on a trend analysis of data from the past half century (*Journal of Hydrometeorology*, February 2004). Higher temperatures increase the atmosphere's ability to hold air moisture, as described in the climate regimes section of GWS. Evidence indicates this projected increase in air moisture and extreme precipitation events already is occurring globally, as noted in the 2007 *IPCC Summary for Policymakers*.

continued on page 4

GW overview, continued

The IPCC summary also acknowledges a correlation since the 1970s between rising sea surface temperatures and an increase in intense hurricanes in the Atlantic, and possibly in other regions, although it notes the data is less reliable for other parts of the world (see GWS, page 26). Remnants of hurricanes from the East Pacific affect the Southwest, as described on page 29 of GWS. These tropical storms can blanket the region with days of rain, increasing the risk of large-scale floods compared to the smaller scale monsoon thunderstorms.

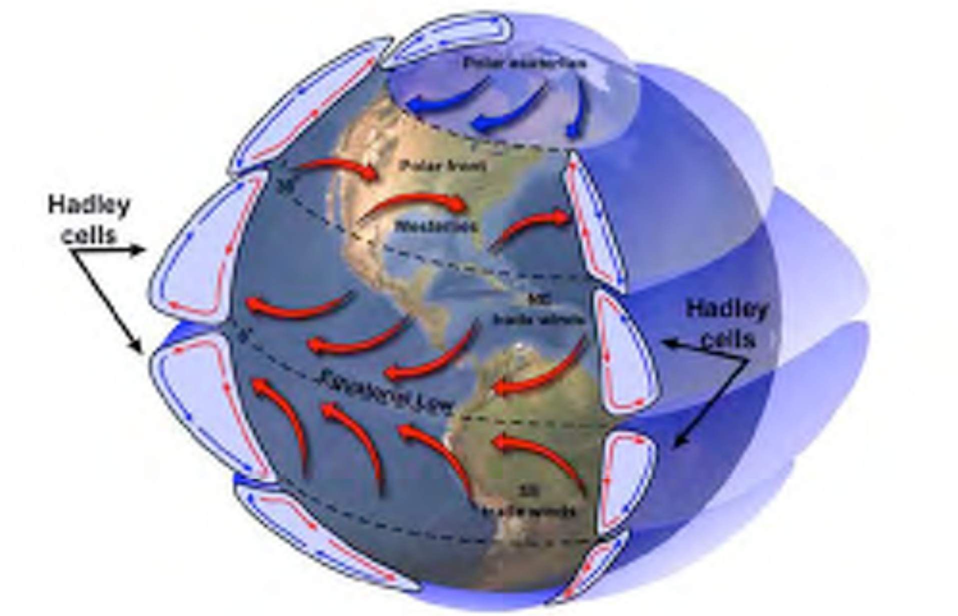

Figure 2. Hadley Cell circulation, above, illustrates how the rising air in the superheated tropics descends in the subtropics, which include the U.S. Southwest. The descending air creates high pressure zones that increase evaporation rates while restricting the development of clouds and rain. This circulation pattern is projected to intensify with global warming. Credit: Barbara Summey, NASA Goddard Visualization Analysis Lab

Impacts on water supply

The growing consensus that the Southwest faces extensive drought in coming years leads to an increasing conviction that the region's water resources will be strained. The GWS chapters on water resources generally reflect that concern. However, two relevant publications worth noting have surfaced since then.

Researchers Martin Hoerling and Jon Eischeid of the National Oceanic and Atmospheric Administration (NOAA) paint a dire picture of future Colorado River flow (*Southwest Hydrology*, January/February 2007). The authors note that the Palmer Drought Severity Index (PDSI) explains nearly two-thirds of the variability in the Colorado's reconstructed natural flow near Lee's Ferry. They used the average of 18 global climate models to model future PDSI values, then applied these estimates to predict future river flow. They conclude the Colorado's annual flow could drop by half, on average, by about mid-century—dire news, especially considering that almost every drop of the river's current flow is already promised to somebody.

On a brighter note, two of the lead researchers whose 2004 paper had suggested the runoff trickling and streaming into the Colorado River might decline by an average of 16 percent in the coming century updated their results (see GWS, page 36). Their 2006 analysis has a somewhat more positive conclusion.

The paper by Niklas Christensen and Dennis Lettenmaier projected modest declines in Colorado runoff for the near future, through about 2040. By the end of the century, they projected the Colorado's flow would drop by 8 to 11 percent, depending on the IPCC emissions scenario used (*Hydrology and Earth Systems Sciences*, 2006).

"Everybody is consistent that there will be a downward trend, it's just a matter of how much," Lettenmaier elaborated in April, referring to theirs and others' latest projections.

The differences from the 2004 paper relate mainly to differences in seasonal precipitation in the Upper Colorado River Basin as projected by the climate models they employed, which they selected from the IPCC archive as appropriate models became available. While the 2004 climate model they used projected a slight shift from winter to summer precipitation, the 2006 models projected a slight shift in the opposite direction, from summer to winter. Such seemingly minor differences have a major impact because the fraction of precipitation that ends up in streams and rivers is much higher in winter than in summer, Lettenmaier noted.

Impacts of warming temperatures on groundwater resources remain even more difficult to model or project than those on surface water supplies, but researchers worry about ongoing trends linked to snow cover decline (see GWS, page 39).

The earlier snowmelt that had been projected already has been observed at many western sites, as described in a 2005 article that documents how this change has been shifting the timing of rivers' peak flows forward in time throughout much of the West (*Journal of Climate*, April 2005). The fraction of precipitation falling as rain rather than

continued on page 5

GW overview, continued

snow also has increased, although some peaks in northeastern New Mexico have managed to evade this overall trend (*Journal of Climate*, September 2006). A January 2007 review article in the *Intermountain West Climate Summary* goes into more detail about recent research regarding western snow cover and water resources (for link, see box at right).

Landscape impacts

The telltale signs of spring, including melting snow, have been arriving earlier in time around the world (see GWS, page 56). The earlier arrival of spring could disrupt life cycles between paired species, such as plants and their pollinators, or birds and their prey. The premature snowmelt can allow soils to dry out sooner, increasing the risk of drought, insect invasions, and large wildfires.

Temperature has the potential to spur on wildfires for many reasons, some of which are described in the chapter starting on page 62 of GWS. In 2006, researchers reported that the number of large western wildfires tends to move up and down with spring and summer temperatures based on U.S. Forest Service and National Park Services data from 1970–2003 (*ScienceExpress*, July 6, 2006). The ground-breaking paper by Anthony Westerling and colleagues, including the UA's Thomas Swetnam, linked the earlier snowmelt during warmer-than-average springs and summers to an increase in large, western wildfires especially since the mid-1980s.

Researchers had also suspected high temperatures were linked to bark-beetle outbreaks that damaged more than 3.5 million acres of southwestern ponderosa and pinyon pines from 2001 to 2003 (see GWS, page 49). In 2005, UA researcher David Breshears and colleagues documented how high temperatures served as an underlying cause behind an extensive piñon die-off event in the Southwest (*Proceedings of the National Academy of Sciences*, October 18, 2005).

Striving for sustainability

And now for the good news. As the evidence grows that the Southwest and the rest of the world face dire disruptions from global warming, politicians have joined scientists and activists to push for policy changes to reduce the greenhouse gas emissions behind the temperature rise and other chaotic climate changes.

Governments from local to state levels, including Arizona and New Mexico, are setting goals for reducing greenhouse gases emissions. The last section of the compilation describes some of these efforts, (as well as some things individuals can do to reduce their own contributions to global warming). Employing wind energy, solar power, energy and water conservation, water harvesting, and forest mitigation all can increase the odds that society will be able to weather global warming.

The move to renewable forms of energy can even help the economy, as the chapter in GWS on solar and wind energy illustrates. Regional efforts to tap into alternative energy markets might help restore some of the U.S. presence in the solar and wind markets. Currently, these forms of renewable energy are so popular around the world that production is not keeping up with demand.

The world market is gearing up for alternative energy production and other "green" business ventures. Also, companies have been reaping savings by pursuing conservation efforts. Recently Wal-Mart has found that putting sky lights in some of its stores not only saved money on energy bills, it also improved profits. Judging from reports in publications from *The New York Times* to *The Economist*, businesses are increasingly finding that going greener speaks to the bottom line as well as the greater good.

Between the efforts of governments, individuals, and businesses, the U.S. public is starting to embrace the wisdom of reducing its collective greenhouse gas emissions. Increasingly, people are recognizing that stabilizing the global climate amounts to stabilizing the global economy. Americans release among the highest levels of greenhouse gases in the world, on both the per-capita and country level. So this country's efforts really can make a difference in how much the world warms in years to come.

Melanie Lenart is a postdoctoral research associate with the Climate Assessment for the Southwest (CLIMAS). The SWCO feature article archive can be accessed at the following link: http://www.ispe.arizona.edu/climas/forecasts/swarticles.html

Related Links

Global Warming in the Southwest
http://www.ispe.arizona.edu/climas/pubs.html

Intermountain West Climate Summary
http://wwa.colorado.edu/products/forecasts_and_outlooks/intermountain_west_climate_summary/January_2007.pdf

Southwest Hydrology
http://www.swhydro.arizona.edu/archive/V6_N1/

Hydrological Earth Systems Science paper by Christensen and Lettenmaier
http://www.copernicus.org/EGU/hess/hessd/3/3727/hessd-3-3727.pdf

"More Large Forest Fires Linked to Climate Change"
http://uanews.org/spots/sci-12868.html

"Underlying Cause of Massive Pinyon Pine Die-Off Revealed"
http://uanews.org/spots/sci-11731.html

Global warming determined to be "unequivocal"

CLIMAS researcher Jonathan Overpeck discusses a recent United Nations report

By Stephanie Doster

A University of Arizona geosciences professor was among the world's leading scientists to issue a recent climate change report that asserted for the first time that global warming is "very likely" driven by human activity.

Jonathan Overpeck, director of the UA's Institute for the Study of Planet Earth and a coordinating lead author of the United Nation's latest Intergovernmental Panel on Climate Change (IPCC) report, said the document represents an international scientific consensus on climate change.

"The most striking thing to me is that we now have presented a much clearer picture of climate change and its causes, both past and future," Overpeck said. "The word we used for the evidence of climate change and global warming is now 'unequivocal.' That is a very strong statement."

The assessment was released in Paris after 113 governments unanimously agreed to the language in the report.

In the last IPCC report, issued in 2001, scientists concluded that industrial emissions "likely" caused a rise in temperatures over the last century. That warming is manifested in observed increasing air, deep ocean, and sea surface temperatures; melting snow, ice, and permafrost; and rising sea levels, said Overpeck, who also is a Climate Assessment for the Southwest investigator.

"All of these observations and others mentioned in the report are consistent and give us a much firmer basis for asserting that climate change is indeed real and that warming has been significant," he said. "I think everyone is pretty comfortable now in saying that we see the climate change and that you cannot get the kind of climate change we're seeing without human-generated greenhouse gases."

Scientists have observed heat-trapping greenhouse gases in the atmosphere, particularly carbon dioxide and methane, at levels that far surpass those seen in the last 650,000 years, Overpeck said. Unless steps are taken to curb these gases, droughts likely will become more frequent. Hurricanes are projected to intensify, boosting the potential for destruction. Some areas, like the Maldives in the Indian Ocean and Tuvalu, a nation of islands and atolls in the Pacific Ocean, could disappear if sea levels rise just three feet. Much more sea level rise will likely be unstoppable over coming centuries if global warming continues unabated.

In the western and southwestern United States and in northern Mexico, climate models agree that winter precipitation will decrease sharply in this century, Overpeck said. The model projections also align with what has actually been happening in the region over the last several years.

One reason for the drying out is that in the winter, the jet stream and the average position of storms will enter the western United States in a more northerly position, bypassing the Southwest, Overpeck said. On top of that, he said, the West has seen a steady downward trend in late spring snowpack because of warmer temperatures and earlier snow melt. Snowpack acts as the region's natural water reservoir and is especially crucial in the dry period that follows winter. A decline in snowpack and streamflow would cut into water supply resources. And with warmer-than-average temperatures continuing into summer, demand for water would spike further still.

The climate models are less certain when it comes to the future of the monsoon, the region's primary source of summer precipitation, and the El Niño Southern Oscillation (ENSO), which is linked to variability in winter precipitation, Overpeck said.

While the region is expected to dry out, it paradoxically is likely to see larger, more destructive flooding as hurricanes, also known as tropical cyclones or typhoons, intensify in all of the oceans.

The largest floods in the Southwest tend to occur when a remnant tropical storm in the fall or late summer hits a frontal storm from the north or northwest,

continued on page 7

GW “unequivocal,” continued

providing enough energy to wring out the moisture in the remnant tropical storm, Overpeck explained.

Overall, he said, the Southwest should brace for a number of far-reaching climate changes as the planet warms.

“You take all of these things together and you can clearly see in the report a strong case that the western U.S. and particularly the Southwest—Southern California into Texas—will probably be one of the hardest and soonest hit parts of the country,” he said.

Stephanie Doster is an information specialist for the Institute for the Study of Planet Earth. The SWCO feature article archive can be accessed at the following link: http://www.ispe.arizona.edu/climas/forecasts/swarticles.html

Related Links

Climate Change Projections
http://www.geo.arizona.edu/dgesl/research/regional/projected_US_climate_change/projected_US_climate_change.htm

IPCC
http://www.ipcc.ch/

Climate change and Southwest Hydrology
http://www.swhydro.arizona.edu/archive/V6_N1/

UA Global Climate Change Lecture Series podcasts
http://podcasting.arizona.edu/globalclimatechange.html

Jonathan Overpeck ISPE webpage
http://www.ispe.arizona.edu/about/staff/peck.html

UA News release on IPCC report
http://uanews.org/cgi-bin/WebObjects/UANews.woa/5/wa/MainStoryDetails?ArticleID=13547

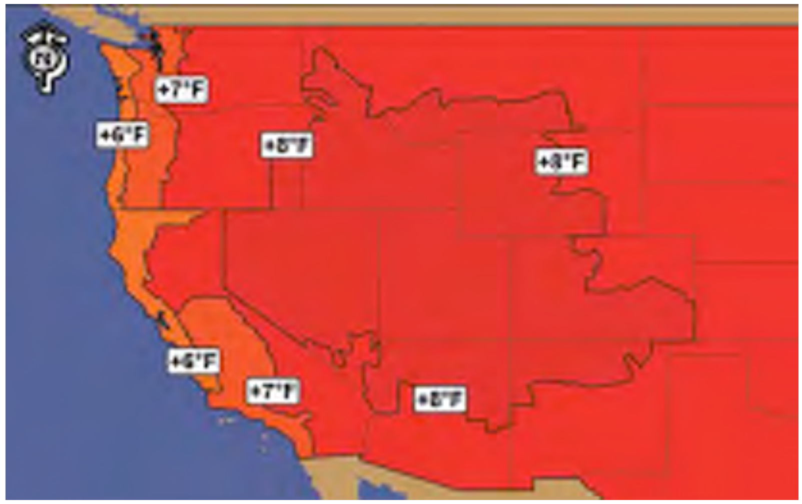

Figure 1. Projected June–August temperature changes from 2091 to 2100.*

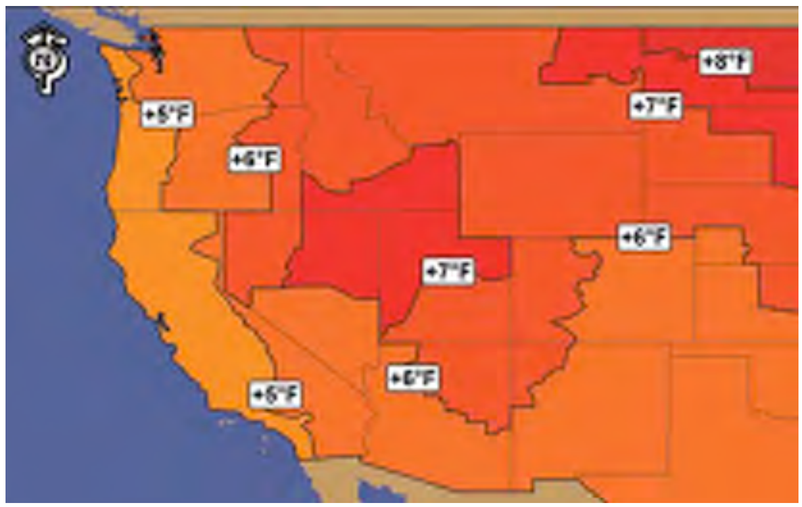

Figure 2. Projected December–February temperature changes from 2091 to 2100.*

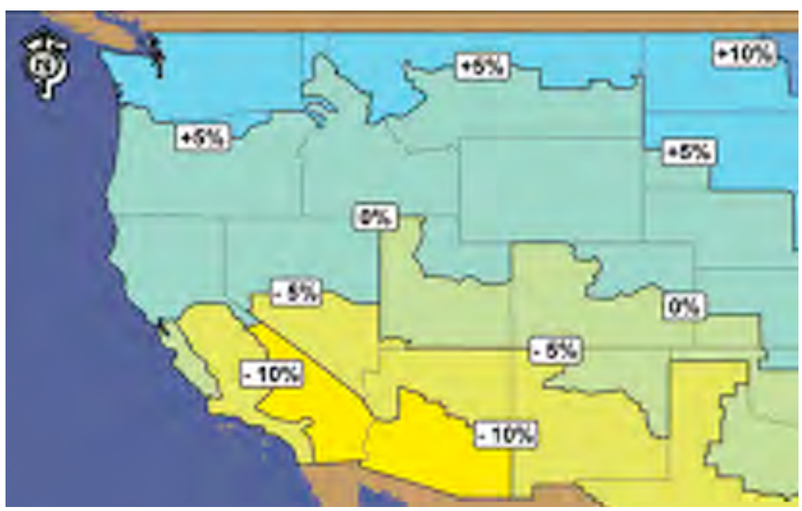

Figure 3. Projected annual precipitation changes from 2091 to 2100.*

**Changes are relative to 1971–2000 averages. Credit: Three maps drawn by JL Weiss, UA; Data from Hoerling and Eischeid NOAA ESRL*

Climate Regimes

Climate Regimes Foreword
By Gregg Garfin

The climate of is the Southwest is the climate of paradox. We are situated in a region where, paradoxically, precipitation varies greatly from year to year, yet remains consistent from decade to decade. Though far from the oceans, ocean circulation dictates much of the variability of our climate. We sit at the crossroads of two very distinct atmospheric flows, the Northern Hemisphere jet stream (the westerlies) coming in from the west over the Pacific Ocean in winter, and the North American monsoon circulation coming in from the south and east during the summer.

During the winter, the westerlies are our friend, bringing multi-day rains that soak into the soil; during the summer they are our enemy, killing the monsoon flow. During the summer, the mountains are our friends, driving moisture high into the atmosphere where it cools and rains down in violent thunderstorms; in the winter, mountains to our west intercept moisture bound for our region.

Much of the character of the climate of the Southwest is determined by a so-called thermally direct circulation, the Hadley Cell, that emanates at the equator, where rising motion brings copious moisture to that region, yet, paradoxically, the "return flow" on the descending limb of Hadley Cell circulation delivers dry air and clear conditions (high pressure) to our region.

While these conditions lend us a climate desired by retirees and winter vacationers, we barely eke out enough precipitation to keep our forests from burning and our streams flowing. Without importing or conveying substantial volumes of water over long distances, so we do not deplete precious groundwater resources, we would not be able to sustain much of the economic activity that makes our region thrive.

It is against this background of a climatically precarious geography that we measure the potential impacts of global warming on our region. The chapters in this section examine the observed and potential effects of warming temperatures on the atmospheric and oceanic circulations that bring (or do not bring) moisture to the Southwest.

Right off the bat, we learn that multiyear to multidecade drought is a fact of life for our region. Measured in both the instrumental record of the last 100 or so years, and the paleoclimate record of at least the last 1,000 years, drought has been with us and will remain with us. And while that last statement may seem like a no-brainer, we learn that the character of drought may be changing.

We can appreciate the virtues and menace of rising temperatures as a factor in the hydrology of the Southwest. Increasing temperatures add vigor to the hydrologic cycle and allow the atmosphere to hold more moisture. However, climate models

continued on page 10

continued

show that increasing temperatures also push the Hadley Cell further north, intensifying drying where middle latitude and subtropical regions meet – such as in the U.S. Southwest. Increasing temperatures also alter snow hydrology, leading to early snowmelt and less winter precipitation arriving as snow at mid-elevations.

Two chapters examine potential changes in the North American Monsoon. These chapters shed some light on a phenomenon that, while characteristic of our region, is also notoriously difficult to predict – even in the absence of global warming. Rising sea surface temperatures (SSTs) in the Gulf of California and diminishing western North America snowpack could lead to earlier and longer-lasting monsoon seasons. The mechanisms appear to be increased moisture surges (Gulf SSTs), and greater pull of moisture from the south through enhanced land surface heating (diminishing snowpack).

However, the notoriously complicated monsoon also depends on the behavior of westerly wind belts to the north and easterly wind belts to the south of the Southwest. Moreover, the impacts of changing ocean temperatures, land surface heating, and winds will probably differ between Arizona and New Mexico. The bottom line, according to these chapters, is don't bet the farm on global warming contributing to a stronger monsoon throughout the Southwest.

Two chapters on hurricanes, including East Pacific tropical storms (which in some years deliver abundant autumn rains to the Southwest), round out the section's synthesis on global warming's observed and potential effects on the climate of the Southwest. Following Hurricane Katrina in 2005, much attention was focused on global warming's effect on hurricanes and tropical storms. While the power of Katrina, or any individual weather event, cannot be attributed to global warming, it appears likely that hurricane intensity has been increasing, and will continue to increase, as ocean temperatures increase.

East Pacific tropical storms, and even their remnants travelling in the westerly wind belt, can deliver significant precipitation to the Southwest. Probably most notable were October tropical storm remnants in the wake of the 1982-83 El Niño; these storms lead to widespread flooding and infrastructure damage in many Southwest towns and cities. The chapters on tropical storms bring to light interesting findings from the leading edge of the atmospheric and oceanographic sciences.

Gregg Garfin is deputy director for outreach at the University of Arizona's Institute for the Study of Planet Earth and a climatologist with the UA Climate Assessment for the Southwest. His research interests include climate variability, drought, and the effective delivery of climate science to decision makers.

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Southwest Climate Outlook
December 2003
THE UNIVERSITY OF ARIZONA®

Southwestern drought regimes might worsen with climate change

Will long-term drought in the Southwest be the rule or the exception as the global climate warms? That's a tough question, because the answer requires a long-range projection based on a climate change that has not yet fully manifested. But there are indications that drought and other extreme events will become more common in a warming world—even if precipitation in the Southwest actually increases, as arguably could be expected.

The global warming trend that climatologists and physicists have long predicted because of a build-up of greenhouse gases began in earnest in the past quarter of a century, and evidence indicates it will accelerate (see sidebar on page 3).

Just how the warming might influence drought regimes was the topic of a workshop discussion that drew about 60 scientists to Tucson in mid-November. Although the group noted that our existing level of understanding prevents accurate predictions of expected precipitation changes by region, they agreed there was much cause for concern because of the global implications.

"Global warming contributes to more drying and heat stress. Going along with the consequences of drought in summer are heat waves and wildfires," noted Kevin Trenberth, a senior scientist who heads the Climate Analysis Section for the National Center for Atmospheric Research.

Trenberth co-organized the drought workshop along with Jonathan Overpeck, the director of the Institute for the Study of Planet Earth (ISPE) in Tucson. While Trenberth focuses on understanding climate processes using computer models and in providing a conceptual framework for observations of drought, Overpeck specializes in using past climates to reveal patterns of climate variability.

"The more we look, the more we find megadrought," noted Overpeck. Like drought, megadrought doesn't have one specific definition, but typically it refers to droughts that persist for decades in one region. "From the perspective of the past, we know that droughts in excess of even 20 years have occurred, so that's a possibility in the future."

Based on workshop discussion and other input, there are two main ways in which global warming could affect drought regimes:

1) Greater heating leads to higher evaporation rates and higher temperatures that boost the atmosphere's ability to hold moisture. This speeds up the hydrological cycle, leading to more drying as well as more high-intensity rainfall and snowfall events.

2) More importantly but less predictably, changes in sea surface temperatures affect the oceanic cycles, such as El Niño, that apparently dictate where the large-scale drought events predominate.

Ramped-up water cycle

Changes in evaporation rates with temperature are fairly predictable. More incoming solar radiation is used up in evaporation than in warming the Earth's surface, Trenberth noted, and the atmosphere's water-holding capacity increases by roughly 4 percent for each rise of 1 degree Fahrenheit.

All those sunny southwestern days lead to high evaporation rates here in winter as well as summer. Even higher evaporation rates might jeopardize the recharging of groundwater, and also make southwestern forests even more susceptible to catastrophic wildfires.

Surface water supplies could also suffer, although that is less predictable because of the expectation for more precipitation in a warmer world. Higher evaporation rates over the ocean translate to more precipitation over land as well as sea, although the effect will surely vary by region. In addition, climatologists expect to see more high-intensity events that do not necessarily soak into the soils, but could help rivers flow more often.

Summer monsoon rain events in the Southwest often fall into the intense category, with sudden downpours that can fill rivers and even streets in the short term. But the effect is so short-lived that monsoon rains generally do little to boost groundwater supplies. Winter precipitation—with

continued on page

Climate Change, continued

snowfall being particularly important to Southwest water supplies—tends to involve less-intense several-day events over larger areas than the splashy, localized summer rainfall.

Even if the Southwest does receive more precipitation overall, there's still a chance of getting more droughts because of the other changes. In fact, workshop participant Russell Vose presented evidence that the higher temperatures may already be impacting drought incidence in the Southwest.

"Temperature, in theory, could have a very significant impact on the extent of area under drought," he said. Jay Lawrimore, Vose, and some of their colleagues at the National Climatic Data Center (NCDC) in North Carolina decided to test the theory by comparing the actual U.S. area under drought from 1998 through 2002 to the theoretical area that would have been under drought if temperatures had not risen as abruptly as they did during the last few decades of the 20th century.

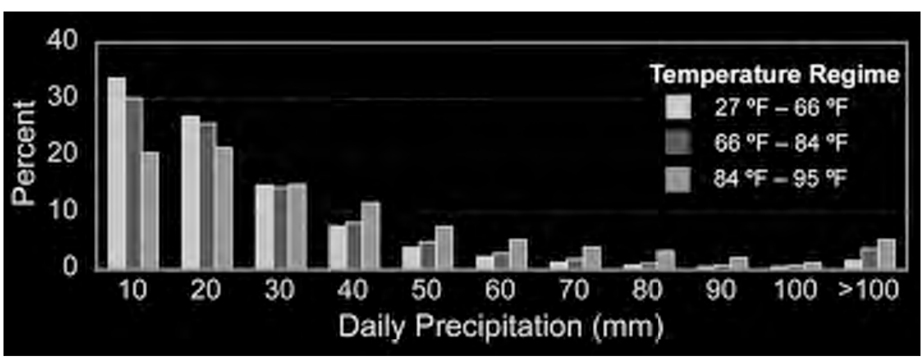
In an analysis applying the Palmer Modified Drought Index to the Four Corner states identified as the Southwest (Arizona, New Mexico, Colorado and Utah), they estimated that about one-fifth less of the land area would have experienced severe to extreme drought from 1998 through 2002 if temperatures had remained on its pre-1976 track. As it was, about three-fifths of the Four Corners land area fell under severe to extreme drought at some point during that five-year time period.

Vose and his colleagues also noticed a national trend for increased precipitation during the last 50 years of the past century. Further, they reported that other NCDC analyses indicated that extremely wet months were increasing even more than extremely dry months in six of the nine regions of the United States, including the Four Corners region.

In addition to spawning more precipitation, a warmer climate likely produces more rainfall relative to snowfall, while warmer spring seasons could cause more rapid snowmelt. So along with drought, floods could well become more frequent as the world warms.

In fact, a 1,000-year climate reconstruction for the Southwest supports the old adage that droughts end with floods, reported Malcolm Hughes of the University of Arizona's Laboratory of Tree-Ring Research (LTRR).

"Please notice that in all of these periods, sustained drought is followed by a sustained wet period," Hughes instructed, referring to the half a dozen intense, prolonged southwestern droughts scattered throughout the millennia in the climate reconstruction he prepared with LTRR colleague Fenbiao Ni and others. (CLIMAS provides reconstructions for Arizona and New Mexico climate divisions at http://www.ispe.arizona.edu/climas/research/paleoclimate/product.html..)



Precipitation events tend to come in more intense bursts in warmer climate, as illustrated by this bar graph from 100 weather stations around the world. Seasonal precipitation for all locations averages about 9 inches (230 millimeters). Yet precipitation in the warmer locales was more likely to arrive in heavy (greater than 40 millimeter) or extreme (greater than 100 millimeter) events compared to the cooler locales. Temperature ranges were converted from Celsius and are approximate values only. Source: Karl, T., and K. Trenberth. 2003. *Science*, 302:1719–1723. Reprinted with authors' permission.

Oceanic influences

While the atmosphere moves lithely around the globe, discharging moisture within about nine days of its capture, the ocean moves on slower time scales that can be measured in years, decades, even millennia. But scientists are still working out numerous details involving the ocean's role in climate.

El Niños, which are particularly important for Southwest winter precipitation, typically occur every three to seven years, but evidence indicates that the frequency of El Niños can vary through time.

El Niño tends to bring periods of above-average precipitation to the Southwest, while its counterpart, La Niña, brings dry spells even more predictably. El Niño conditions occur when a warm tongue of surface water reaches the eastern tropical Pacific, while La Niña conditions describe times when the warm pool remains particularly concentrated in the western tropical Pacific.

Although our understanding of the El Niño phenomenon has grown enough to allow prediction of its arrival months ahead of its influence, the details remain uncertain for what to expect with a warmer climate.

"I think it's clear that El Niño will be changed as the climate changes," Trenberth said. "And our observations of El Niño suggest that it has changed in the past 20 years. However, our climate models, which we like to use to

continued on page 13

Climate Change, continued

verify that these two things are related, are really not up to the task at the moment."

"Coupled" computer models try to recreate the atmospheric-ocean link, but with limited success. For instance, changing atmospheric temperature even in coupled computer models is not enough to reproduce some of the decades-long droughts of the past. Modelers must instead specify observed sea surface temperatures as well to recreate these droughts. This highlights the importance of the ocean but also signals our lack of understanding about what causes sea changes.

An increase in intense El Niño events in the past quarter century, along with an expectation of more frequent and stronger El Niños in the future, supported a conclusion by a regional panel that climate change would bring more precipitation to the Southwest. The Southwest Regional Assessment Group, co-chaired by then-ISPE Deputy Director William Sprigg, used this premise to predict other future changes in their 2000 report (available online at http://www.ispe.arizona.edu/swassess/). However, some climate models show an increased frequency of El Niño during cooler time periods.

The question is further complicated by evidence that all of the world's oceans have been warming since about the middle of the 20th century, as reported in a March 24, 2000, *Science* article by Sydney Levitus and colleagues at the National Oceanographic Data Center in Maryland. Their finding indicates that the ocean warming preceded the atmospheric warming trend that began in full swing in the mid-1970s.

This indication that oceanic warming preceded atmospheric warming makes perfect sense to Trenberth, who suspects the high sea surface temperatures measured during the strong El Niño of 1997–1998 helped put 1998 down in the books as the hottest year on record, as the heat moved from the ocean to the air. Interestingly, this high-magnitude event quickly switched into a high-intensity La Niña event from 1998–2002, which contributed to drought conditions in the Southwest.

Martin Hoerling, another workshop participant, published a paper in the January 31, 2003, issue of *Science* attributing the severity of the 1998–2002 drought—which spanned southern Europe and Southwest Asia as well as the southwestern United States—to persistently warm sea surface temperatures in the western Pacific and Indian oceans during this time frame.

If warm temperatures in the Pacific can strengthen both sides of the El Niño cycle, the theory that a warming climate will bring more extreme events gains strength. The uncertainty about how ocean cycles might change with the continued warming, in turn, fuels concerns that the global climate could make an "abrupt" shift to a new state—a quantum leap that would force scientists to re-evaluate the current system of knowledge about climate.

"In terms of abrupt climate change, we now think that it's the wild card of global warming or future climate change," Overpeck said. "There is good reason to suspect that with climate change, the tropical Pacific system could change abruptly in ways that we can't yet anticipate."

–Melanie Lenart, CLIMAS

Next month, the newsletter will address how other oceanic trends, the Atlantic Multidecadal Oscillation and the Pacific Decadal Oscillation, can influence Southwest climate.

Evidence Of Global Warming

The 1990s and some of the years that followed contained an abundance of exceptionally hot years, as judged by both the instrumental record and longer records reconstructed from tree rings, corals, ice cores, and other natural archives of temperature.

By all accounts, global mean annual temperatures since about the mid-1970s have been above average. Since about 1976, the rate of atmospheric warming has tripled the 20th century average global rate of about 1 degree Fahrenheit per century, as captured by analyses by Russell Vose and his colleagues at the National Climatic Data Center.

And given the continuing input of greenhouse gases entering the atmosphere from industry, vehicles, and deforestation, scientists expect the warming trend to continue and even accelerate throughout the 21st century. Greenhouse gases like carbon dioxide and methane basically trap some of the sun's heat that would otherwise escape from the atmosphere out into space.

The Intergovernmental Panel on Climate Change projects the influx of greenhouse gases will spur a rise in global temperatures by roughly 2 to 10 degrees Fahrenheit by 2100.

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THE UNIVERSITY OF ARIZONA®

Scientists look to ocean for clues about drought

BY MELANIE LENART

The landlocked Southwest does not escape the ocean's reach. Although scientists continue to untangle how these sea changes affect southwestern climate, what they've learned so far is chilling. Both the Pacific and Atlantic Oceans appear aligned to favor long-term drought in the Southwest.

These are the major oceanic fluctuations that appear to influence regional climate:

- The El Niño Southern Oscillation (ENSO), centered in the tropical Pacific. While "El Niño" (and its opposite, La Niña) relates to changes in sea surface temperatures, the "Southern Oscillation" refers to the associated patterns of atmospheric pressure over the tropical Pacific.
- The Pacific Decadal Oscillation (PDO), identified by changes in sea surface temperatures further north in the Pacific Ocean.
- The Atlantic Multidecadal Oscillation (AMO), identified by changes in sea surface temperatures averaged over the North Atlantic from the equator to 70º North.

If ENSO is the poster child of oceanic influences on climate, the AMO and PDO are the new kids on the block. Scientists began only in the mid-1990s to document the relation between North American climate and the long-term Atlantic changes captured by the AMO. They are still hammering out a consensus on its features, its climatic effects, and whether it even exists as an identifiable physical process. Similarly, researchers are still trying to pinpoint the reasons for PDO fluctuations and the scale of its reach.

The index researchers use to detect the AMO is actually a 10-year running mean of North Atlantic sea surface temperature, and its climatic effects do not show up in year-to-year analyses. They only emerge when climatic data are lumped together into decades, a process known as smoothing because it reduces year-to-year spikes.

But the correlation between long-term drought in the continental United States and the AMO warm phase appear real enough in both the instrumental record and longer records based on tree rings and other proxies, noted Julio Betancourt, one of the scientists at the forefront of this research. Betancourt is a researcher at the U.S. Geological Survey's Desert Laboratory in Tucson.

"If the North Atlantic warms, then you're nailing summer precipitation across much of the continent. Drought in May and June, the peak months of precipitation in the Plains and Front Range, can be followed by a weak monsoon season across the Southwest in July and August," Betancourt explained.

Unlike the AMO, the Pacific Decadal Oscillation does show up in tests for annual effects on climate, although it's still unclear whether the PDO rates as its own phenomenon or merely serves as a memory bank of dominant ENSO patterns. The "cool" phase of the PDO is associated with low precipitation in the Southwest, especially during the winter—much like an extended La Niña event.

But while ENSO typically switches from El Niño to La Niña conditions and back again within three to seven years, the PDO and AMO take more like three to seven decades to go full circle.

When a "cool" PDO phase lines up with a "warm" AMO phase—as it did in from 1998 to mid-2002—the result can be year-round, persistent drought in the Southwest, Betancourt said (see Figure 1).

This "double-whammy" effect also helps explain how things got so dry during the 1950s drought, Betancourt indicated. The proportion of Southwest area besieged by drought neared 100 percent (see Figure 1) before the welcome relief carried in by a strong El Niño event in 1957–58. For this analysis, the Southwest includes Arizona, Colorado, New Mexico, Utah, and parts of Texas and southern Oklahoma.

The AMO moved into a warm phase in 1995, just before precipitation in Arizona and New Mexico began to falter. The PDO switched into a "cool" phase in the summer of 1998.

On a positive note, the PDO has switched back into gray territory, for the moment at least. In August 2002, values switched from negative to positive, according to an index posted on the National Oceanic and Atmospheric Administration website.

Positive PDO values can mean good news, heralding a Southwest-friendly "warm" phase, when maintained for the better part of a decade or so. But

continued on page 15

Drought clues, continued

Betancourt doesn't believe the Southwest will be released from the current drought's stranglehold quite so easily. One phase of the PDO typically lasts about 20 or 30 years, while one phase of the AMO usually lasts about 30 or 40 years.

Still, the research to identify the mechanisms behind the oscillations—and therefore improve the chances of using these indices for long-term climate forecasting—remains in the early stages.

"On a decadal basis, it comes up very clear. But the AMO and PDO oscillations are so long. We don't know what the mechanisms are that make them shift," noted U.S. Geological Survey researcher Gregory McCabe, who is an author with Betancourt and others on an upcoming paper describing how AMO and PDO patterns relate to long-term drought frequency in the United States.

McCabe believes researchers eventually will discover a physical reason behind the oceanic oscillations. On the other hand, those who see the PDO as a long-term expression of ENSO variability rather than a physical process in its own right include Michael Dettinger, a U.S. Geological Survey researcher and co-author with McCabe on a 1999 article that related ENSO to the PDO.

When heat is concentrated in the tropical Pacific, as during an El Niño event, a side effect is a cooling of the northern Pacific, Dettinger explained. The situation generally reverses during a La Niña event. The PDO phase reflects whichever ENSO phase has been most dominant when measured over decades instead of year to year, he suspects.

"The North Pacific is like a huge flywheel that takes a long time to spin up and get going in that direction," he added. "But once it gets going, it takes a long time to wind down."

Of the two long-term oscillations, the PDO has the advantage of having an identifiable relation to Southwest climate. Dettinger believes the climatic effects hold regardless of whether the PDO is a separate process from ENSO.

"The Southwest and western North America get most of our weather from the winds and storms and jet streams that come across the North Pacific to reach North America," he said. "What that means is that even if the PDO were solely driven by the ENSO process, the shape that those processes give to the North Pacific is the most immediate source of our weather."

The naming of PDO phases follows ENSO conventions, with a "cool" event referring to relatively cool sea surface temperatures extending from

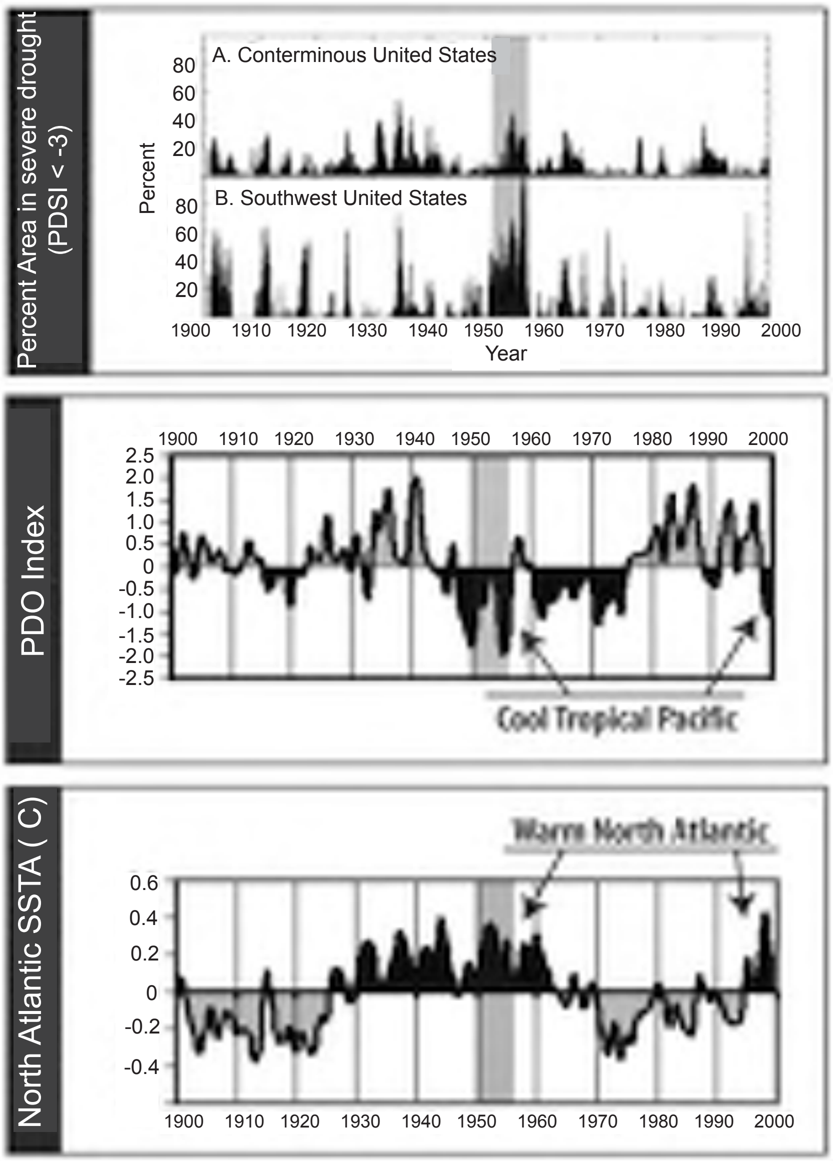

Figure 1. Opposing shifts in tropical Pacific and North Atlantic Ocean temperatures may foretell persistence of disastrous, multiyear droughts across the North American continent. During most of the 1950s, drought conditions characterized the Southwest (top), which in this analysis includes Arizona, New Mexico, Utah, Colorado and parts of Texas and Oklahoma. The gray shading shows the same time frame in all figures, including those of two indices that appear linked to long-term drought in the Southwest, the PDO (middle) and AMO (bottom). The indices returned to their 1950s pattern in 1999, which some see as an ominous sign that long-term drought may be in store. All figures provided by Julio Betancourt.

the tropical Pacific along the western U.S. coast, and relatively warm sea surface temperatures across the majority of the North Pacific. So, despite the nomenclature, the Southwest suffers a lack of precipitation when warm sea surface temperatures dominate (on a decadal scale) in the northern waters of both ocean basins.

In contrast, the relatively cool sea surface temperatures that occur in the northwestern Pacific during a "warm" event displace the jet stream southward, generally to the advantage of Arizona and New Mexico. In addition, the associated warm tongue of water along the West Coast, which comes up from the tropics, supplies moisture for storms.

"The Pacific has really ruled our thinking for the last few decades," Betancourt said. It's more difficult for scientists to accept the idea of an Atlantic influence on Southwest climate because prevailing winds in the mid-latitudes come from the west and southwest, rather than the east, he added. But he believes the strong correlations he and others are finding between AMO patterns and decadal drought will prove convincing in the end.

David Enfield, an oceanographer with the National Oceanic and Atmospheric Administration and one of the first researchers to examine the climatic effects of the AMO, suspects the Atlantic changes influence climate by changing the steering pattern for weather over the continent at 500 millibars (at about 16,000 feet on average). As he and colleagues reported in a 2001 article, the AMO warm phase is associated, for the southern portion of the continent, with a higher than usual atmospheric ridge over the West Coast and increasingly lower pressure in an eastward direction.

Enfield has also found correlations between the AMO and ENSO patterns. In fact, all three oceanic fluctuations appear to influence each other to varying degrees in ways that are difficult to isolate in time and space.

How might climate change affect these fluctuations? At this point, climate models give mixed results even when predicting how global warming might affect ENSO, which is understood and accepted much more than the PDO and AMO. So the jury is out when it comes to predicting the effect of global warming on oceanic fluctuations in general.

"We don't even have the first principles down," noted Dettinger, alluding to the mechanistic principles governing these oceanic oscillations. "So until we get that down, I don't expect to see accurate predictions of what would happen with global warming."

Still, it's interesting to consider that the Intergovernmental Panel on Climate Change generally expects atmospheric warming to be greater in northern latitudes than in the tropics. As noted earlier, relatively warmer sea surface temperatures in the North Atlantic and North Pacific do not bode well for Southwest precipitation.

On the other hand, an increase in El Niño frequency or intensity—which many researchers expect based on their admittedly incomplete understanding of the process—could improve Southwest precipitation patterns both at the annual scale of ENSO events and the decadal scale of the PDO.

Given the uncertainty, Southwest residents would do well to assume the worst when it comes to making preparations for drought, McCabe suggested.

"It seems that we've been living in an anomalously wet period," McCabe said. "If we even go back to normal, are we going to be able to withstand it? It's kind of frightening now, with increased population and water demand. It will be interesting to see how we survive a 1950s-like drought."

Related Reading

Newsletter articles

"PDO: Where will the footprints lead?" END InSight newsletter story available at http://www.ispe.arizona.edu/climas/forecasts/articles/PDO_Oct2002.pdf

"Predicting El Niño," END InSight newsletter story available at http://www.ispe.arizona.edu/climas/forecasts/articles/predictelnino_Dec2002.pdf

"Southwest drought regimes might worsen with climate change," Southwest Climate Outlook newsletter story available at http://www.ispe.arizona.edu/climas/forecasts/articles/climatechange_Dec2003.pdf

Websites

National Oceanic and Atmospheric Administration website to access indices for ENSO, PDO, and AMO, among others: http://www.cdc.noaa.gov/ClimateIndices/

Journal articles

Delworth T. L., and M. E. Mann. 2000. Observed and simulated multidecadal variability in the Northern Hemisphere. *Climate Dynamics* 16:661–676.

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El Niño: a wild card for climate change impacts

Place your bets on El Niño's influence in the Southwest

By Melanie Lenart

The Southwest has always had its appeal for gamblers. In the Old West, gunslingers frequented saloons to play poker games like Three Card Monte, undaunted by the prospect of taking a bullet for a questionable winning streak. In modern times, Black Jack players from distant counties flock to the casinos sparkling through the night on tribal lands, praying for a reign at the table.

In the desert, there's another gamble that we all take: Will the rains that have sustained us in modern times continue to replenish our water supplies? Will global warming deal us a losing hand, with the coming decades bringing us more dry wells and shrinking lakes? Place your bets.

If climate is your strong suite, it will come as no surprise that the fate of southwestern water supplies rests largely in the hands of El Niño—and El Niño remains a wild card in the context of climate change. If El Niño events predominate, as they did during a wet period from about the mid-1970s through the mid-1990s, southwestern reservoirs and aquifers alike could benefit from the general boost to winter precipitation (Figure 1). But if La Niña events dominate as they did during the drought years 1998 until 2002, the growing population of the Southwest could be in for some dry times (Figure 2).

When trying to predict the general climate of the next several decades, arguments have been raised for a wide range of scenarios, including dominance by El Niño, an overall trumping by La Niña, stronger fluctuations between the two, and weaker events for both conditions.

Climate models conflict

"The bottom line is we don't know what climate change will do to El Niño," explained Henry Diaz, a climatologist with the National Oceanic and Atmospheric Administration's Climate Diagnostics Center. "Most general circulation models, in fact, don't have a good representation of the El Niño phenomenon—although the latest models are showing substantial improvements."

Modeling El Niño is particularly challenging because it requires "coupling" the ocean and atmosphere into an interactive system. Trade wind activity helps define El Niño, which is why climatologists prefer to call the linked ocean and atmospheric system by one phrase, the El Niño–Southern Oscillation (ENSO). The linkage is easier said than done in climate models.

Several climate models project an eventual dominance by El Niño events, but often for different reasons, as the Intergovernmental Panel on Climate Change noted in its latest report in 2001. This international consortium of scientists resisted reaching a conclusion about whether El Niño will hold sway. The panel pointed to more ambiguous models and an analysis by Mark Cane and his colleagues that showed the potential for a La Niña-like response from the warming temperatures for at least a few decades to come.

While considering how these patterns might fluctuate with global warming—a speculative venture in any case—it's useful to consider how the patterns work now. During El Niño events, the Peruvian side of the tropical Pacific Ocean tends to register higher-than-usual temperatures at the ocean surface along with a slackening off of easterly winds. During La Niña events, the sea surface temperatures in the same region tend to run even cooler than usual, with the associated strong easterly winds pushing away the warm surface layer and exposing the cooler waters below.

Warm sea surface temperatures tend to generate storm clouds, while anchoring winds direct where the clouds travel. Along with the tropical trade winds, which flow east to west near the equator, El Niño fluctuations influence the mid-latitude westerly winds. The westerlies flow from the Pacific across the continental United States, favoring the Pacific Northwest during La Niña years and the Southwest during El Niño years.

A shifty character

However, the degree to which El Niño influences specific regions can change in time, according to a 2001 International Journal of Climate paper by Diaz and two colleagues comparing ENSO impacts on many regions of the globe. Using the most reliable instrumental records for land (and thus going back only to 1948), they saw shifts in the character of El Niño impacts.

"It's not your grandfather's El Niño anymore," as Kevin Trenberth, an atmospheric scientist with the National Center for Atmospheric Research, put it. El Niño could undergo additional character changes as the climate warms, he suggested.

Diaz noted that it could take decades or more before El Niño settles into a mode characteristic of a global warming pattern. "We don't know the exact shape of the form that it will take," he added.

continued on page 18

El Niño, continued

In the meantime, the debate about how the ocean system will react in the next few decades to the ongoing global warming seems to revolve around two alternative lines of thinking: One is that stronger and/or more frequent El Niño events could predominate and serve as a means for cooling the planet in the long run, as much of the heat released from the ocean during El Niño years eventually makes it way out into space. The other is that a predominance of La Niña events could help the planet strive for equilibrium in the face of the global warming, with the ocean basically absorbing some of the incoming heat into deeper waters while presenting a cooler surface to the atmosphere.

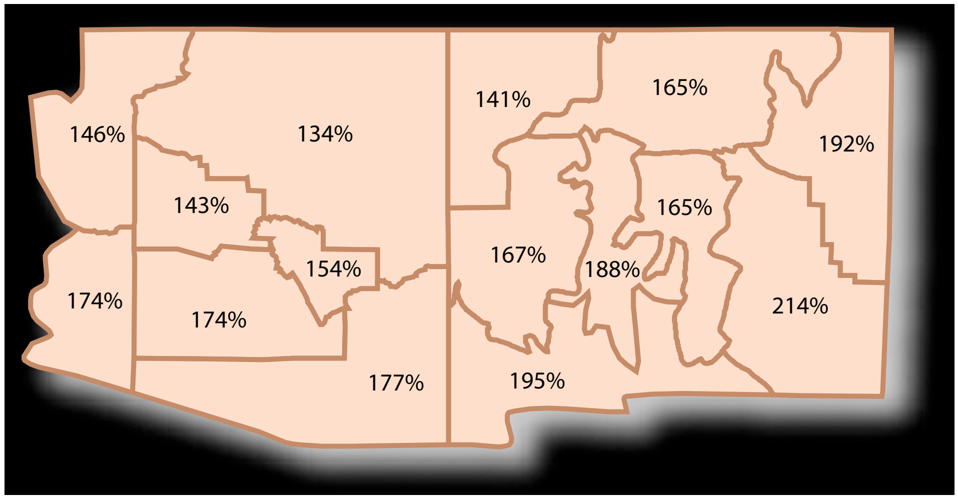


Figure 1. During El Niño years, all climate divisions in Arizona and New Mexico tend to receive above-average winter precipitation, as shown above. Values represent the percentage of December–March precipitation falling during El Niño years compared to non-El Niño years for the period 1895-1996. Source: adapted from NOAA Climate Predition Center material.

El Niño vs. La Niña

Saturday Night Live fans may remember a skit where Chris Farley played El Niño (translation: "The Ninyo") as a leotard-clad boxer ready to rule the ring. Images like this helped popularize the term in the 1990s—as did the dominance of the real El Niño in the Pacific between 1990 and 1995 and again in 1997 through 1998.

The predominance and strength and evolution of El Niño events since about 1976 has been highly unusual in the record since 1880, Trenberth argues. He and others made this case in papers released in 1997 and 1998, before the extreme El Niño event that spanned those years made the record books, and in a subsequent *Journal of Climate* paper in 2001.

Many view the mid-1970s as a turning point, a time when global warming from human activities such as burning petroleum products and forests really took root. Some call this turning point the 1976–1977 climate shift. The predominance in El Niño conditions since the mid-1970s might suggest an influence from human-launched global warming, Trenberth indicated. If so, this could imply that El Niño might remain dominant if the atmosphere continues to heat up as projected.

On the other hand, Mark Cane and others have argued that El Niño events in the late 19th century were on a par with recent decades.

"In many ways, the El Niño of 1877 was certainly far more destructive and had more serious consequences than any of the recent ones," explained Cane, a climatologist with Columbia University's Lamont-Doherty Earth Observatory. He noted that it appears to have contributed to the failure of the Indian monsoon that year, among other deadly disasters.

Cane points to evidence in records of fossil corals to argue that ENSO fluctuations have varied throughout the centuries and even millennia, with the latter based on spotty individual coral segments that date back as far as 130,000 years. Some of the century-scale results imply a predominance of La Niña events during previous warm periods, Cane suggests.

Will El Niño rule?

Several lines of analysis agree that El Niño serves to release heat from the ocean, with the short-term effect of warming the atmosphere but the long-term effect of cooling the planet.

Like others before and after them, Diaz and colleagues found the tropics registered the most warming during El Niño events of the past half a century. The Tropics of Cancer and Capricorn delineate the 40 percent of the planet that seasonally faces the sun head-on, thus receiving the full blast of its power without any angling to soften the blow. Meanwhile, they found the "extratropical" regions showed more variability, typically registering either average or even cooler-than-average temperatures.

Trenberth has pointed out that the record-breaking temperatures of 1998 occurred as an El Niño event that started in 1997 and stretched into 1998 as well. The year 1998 was the warmest year on record globally, with 2005—which featured a weak atmospheric El Niño event—shaping up as a contender for either the top spot or second-hottest year in the instrumental record.

In the long run, though, El Niño eventually releases into space some of the heat that had been stored in the planet's oceans, climatologists agree. In fact,

continued on page 19

El Niño, continued

El Niño serves to dissipate heat in three apparently coordinated ways, noted Trenberth in a 1998 paper with lead author De-Zheng Sun, with NOAA's Climate Diagnostics Center. These include ocean dynamics that move warm water from the equator to the subtropics; atmospheric dynamics that export heat to the subtropics, sometimes in the shape of thunderstorms; and cloud cover that helps shield more of the eastern Pacific from direct sunlight.

"This raises the question of whether the very existence of El Niño arises from the need to move heat out of the equatorial Pacific," as Sun and Trenberth wrote in *Geophysical Research Letters*. The equatorial region within the tropics takes the most direct hits of sunlight of any region on the globe.

The case for La Niña

Some propose that La Niña conditions could become more prevalent as the climate warms, at least for several decades. Cane's 2004 review paper, *The evolution of El Niño, past and future*, notes some researchers have found an increase in La Niña events during warm periods.

In fact, an analysis he and others conducted found the eastern equatorial Pacific—the location that most clearly signals El Niño events—was one of the few places on Earth that did not register an overall warming during the past century, he said. This implies that upwelling from La Niña events helped counterbalance the global warming that registered almost everywhere else. However, he and others are still teasing out details that hint at differences in patterns that could actually be consistent with a more El Niño-like nature in the latter half of the century, he wrote in an email message.

During the past, ENSO seems to have served as a means for the Earth system to mitigate the effects of short-term warming or cooling from changes in incoming solar energy or volcanic activity. For instance, a Journal of Climate paper Cane wrote with lead author Michael Mann of the University of Virginia and others suggested El Niño events may have kept oceans warmer than expected in the late 17th Century, during the so-called Little Ice Age.

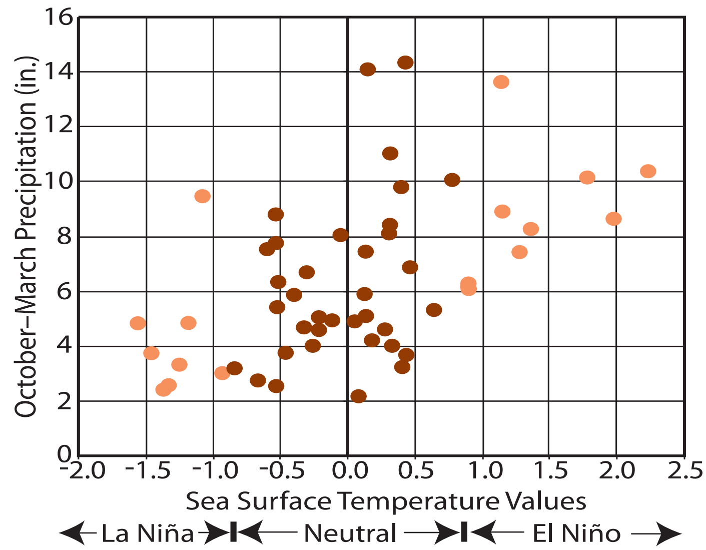


Figure 2: Arizona precipitation. Points represent October–March precipitation tallies, with values from 1951–2003.

Similarly, a predominance of La Niña events may have kept the ocean relatively cool during the late 12th and early 13th Centuries, during the so-called Medieval Warm Period, which appears to coincide with warmer European temperatures at various points during its time span of roughly 900 to 1300 A.D. Tree-ring records show that drought dominated in the West during this time frame, as documented by Edward Cook of Lamont-Doherty Earth Observatory and colleagues in a 2004 paper in *Science*. In fact, one of four lengthy droughts during this time frame centered on 1150, when the ancestors of the modern-day Pueblo Indians abandoned their sophisticated city in Chaco Canyon, New Mexico.

On the other hand, the period from 1950 to 2000 looks a bit different than the trend over the earlier part of the century, Cane acknowledged, making it difficult to draw firm conclusions about how modern climate compares to earlier climate regimes. The general warming during the late 12th and early 13th Century probably resulted from more solar heating combined with fewer volcanic eruptions, he indicated. Meanwhile, climatologists attribute the modern warming mainly to an increase in greenhouse gases like carbon dioxide from burning oil, coal, gas and forests.

"The question is, then, does greenhouse warming work the same way? Is heating just heating, or does it make a difference if it's solar heating or greenhouse heating?" Cane asked.

The fate of El Niño goes beyond a rhetorical question because of its huge impact on precipitation regimes in many regions of the world, including the southwestern United States. Yet there is little we can do to alter El Niño's uncertain fate in the short term. The global warming set in motion particularly since the mid-1970s won't be stopping anytime soon. Even if people changed their ways tomorrow, the extra heat already stored in the deep ocean would carry the warming out for many decades, analyses indicate.

So, what's in the cards for the El Niño, which generally dictates the Southwest's water future? Place your bets.

Melanie Lenart is a postdoctoral research associate with the Climate Assessment for the Southwest (CLIMAS). The SWCO feature article archive can be accessed at the following link: http://www.ispe.arizona.edu/climas/forecasts/swarticles.html

Monsoon could strengthen as climate warms

Broad-scale influences imply more summer rain, but many caveats apply

by Melanie Lenart

Editor's Note:
This is the first in a two-part series about how the monsoon might change with global warming. This article focuses on some of the broad-scale factors that could influence monsoonal strength while next month's article will consider atmospheric influences on the North American monsoon.

The mystery continues about how global warming might impact the North American monsoon, which lofts summer thunderstorms into the Southwest. Some circumstantial evidence suggests future monsoons could strengthen as temperatures rise, but the investigation has barely begun.

It's an important case considering that collectively New Mexico and Arizona receive about a third of their annual precipitation during the peak months of the monsoon, July and August (Figure 1). A major challenge is picking out the most influential suspects in the line-up, especially since they differ somewhat for the two states. Sea surface temperature (SST) definitely has some role in starting things off, while atmospheric response appears to determine where monsoonal rains will strike next.

Considering how climate change might affect the monsoon requires thinking out of the box. The Intergovernmental Panel on Climate Change projects that the world's average annual temperature will rise at an average rate of about 0.2 to 1 degree Fahrenheit per decade this century. But computer programs designed to consider the impacts of this warming model precipitation at grid scales that don't match regional monsoons.

Also, such models typically have 18 or more atmospheric layers, but they have only one land elevation for each grid cell measuring hundreds of square kilometers. This flattens the mountains that are so important to monsoon dynamics, with their slopes angling to take the full force of the summer sun's rays.

Besides North America, monsoons contribute summer precipitation in South America, Africa, Australia, and, of course, Asia. The North American Monsoon actually centers on Mexico, with Central America as well as Arizona and New Mexico receiving only fringe benefits from the main event. The southwestern U.S. region typically affected by the monsoon can expand or contract somewhat depending on seasonal monsoon strength and pattern.

The first fact in the case is that rising sea surface temperatures tend to promote precipitation. At least that's what witnesses have observed, although the physical reasoning for this remains unclear. Global warming will continue to raise sea surface as well as air temperatures. In fact, data provided by the National Climatic Data Center (NCDC) shows that surface temperatures of the world's oceans already rose on average during the second half of the 20th century (Figure 2).

Another line of evidence involves the role of land heating in luring summer wind and rain to parched lands. Land temperatures fluctuate faster than ocean temperatures with a given heat input (Figure 2), and this operates at the scale of decades, as well as seasonally and even daily.

As for exhibit number three: As air temperatures go up, so does the atmosphere's ability to pick up and hold moisture. This well-documented factor leads climate change specialists to predict with confidence that precipitation rates as well as evaporation rates will increase with a warming climate—at the global scale. Regionally, it will vary, and there's little confidence regarding specifics.

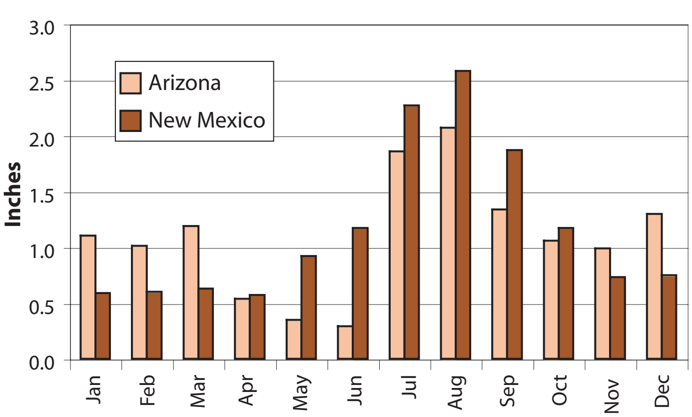


Figure 1. Average monthly values for July, August and September rainfall illustrate the monsoon's substantial contribution to Arizona and New Mexico precipitation. Data is provided by the Western Regional Climate Center, http://www.wrcc.dri.edu/htmlfiles/avgstate.ppt.html.

No smoking gun

There is no clear verdict on how the North American monsoon will fare in a warming world. However, circumstantial evidence suggests monsoons in general will strengthen as global warming heats up ocean and land surfaces and increases air moisture.

All three factors suggest stronger monsoons with a warmer climate—but they also come with complexities. As might be expected, generalities drawn at such a broad scale have limitations for local or regional applications. Still, they're worth considering, with caveats in mind.

Sea surface temperatures

One of the more compelling reasons to suspect an increase in monsoonal strength with time involves the role played by sea surface temperatures in spawning thunderstorms and other convective systems.

continued on page 21

Monsoon, continued

Convection relates to surface heating. A pot of boiling water on a stove demonstrates a form of convection, with the heat from the stovetop being lifted up as bubbles float to the top. This is somewhat analogous to how the atmosphere works when it comes to convective processes.

Rising sea surface temperatures in the Gulf of California contribute to the convective processes that hail Arizona's monsoonal rains, according to research by atmospheric scientist David Mitchell and some colleagues (*Journal of Climate,* September 1, 2002).

Based on their temperature estimates from satellite observations, the sea surface in the gulf must warm up to 26 degrees Celsius (about 79 degrees Fahrenheit) to launch thunderstorms along the Sierra Madre mountains of northwestern Mexico into Arizona. This is also the minimum sea surface temperature required to spawn hurricanes, and for tropical convection in general.

"It's a very interesting number. That's when we get convection started along the coast of Mexico, and all over the world really," Mitchell noted. He cited an October 1993 *Journal of Climate* paper by Chidong Zhang for support.

An even more interesting number, at least for monsoon prediction purposes, is 29 degrees Celsius (about 84 degrees Fahrenheit). Relatively heavy rainfall from the monsoon in Arizona typically begins within days of the northern Gulf's sea surface reaching this temperature, the researchers found.

"We have been monitoring the monsoon since we wrote that paper, and so far the monsoon seems to be consistent with what we'd expect," Mitchell reported by phone. Although he has developed a model to use May conditions to predict this monsoon onset, he was unable to test it this year because he's working off-

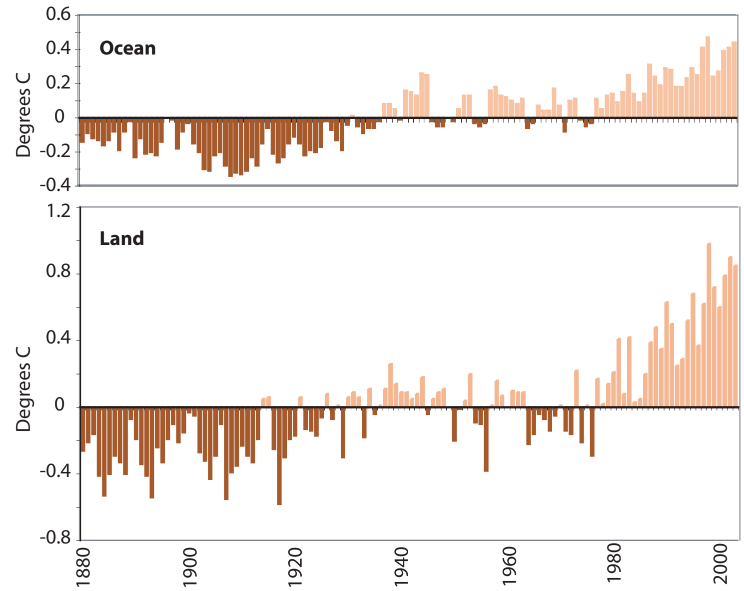


Figure 2. Global mean temperatures compiled by the National Climatic Data Center show an ongoing warming of the planet, with land temperatures heating up faster than ocean temperatures. The annual differences are shown in comparison to the average temperature for 1961–1990. Details about how the data were calculated as well as the data are available at http://lwf.ncdc.noaa.gov/oa/climate/research/anomalies/anomalies.html.

site on a project to improve the treatment of clouds in climate models.

Mitchell's finding that Gulf of California temperatures trigger Arizona's monsoonal rains is supported by another independent study. University of Arizona researchers led by William Wright used oxygen isotopes in tree rings to pinpoint Arizona's monsoonal moisture as coming from the Gulf of California and the eastern Pacific Ocean (*Geophysical Research Letters,* March 1, 2001).

Although Mitchell said he prefers relating northern Gulf sea surface temperatures to monsoon onset rather than strength, he has also found that a late arrival of warm water in the northern Gulf typically means a weaker monsoon for Arizona. If these sea surface temperatures don't reach about 84 degrees Fahrenheit by mid-July, the state's summer rainfall tends to fall below average, he indicated.

A connection between monsoon onset and strength was identified as well by Arizona state climatologist Andrew Ellis and colleagues (*International Journal of Climatology,* February 2004). Their analysis of monsoon seasons from 1950–2001 indicated that early onsets tend to mean longer—and thus wetter—seasons.

The relationships between Gulf of California sea temperatures and monsoon onset do not appear to translate to New Mexico, noted University of New Mexico researcher David Gutzler.

"It's less obvious that that sort of influence maintains its strength, as you move east toward and over the Continental Divide," Gutzler said.

Monsoon strength in Arizona and New Mexico often differ within the same year, leading him (and others) to suspect different influences for the two states. New Mexico's moisture source for monsoonal rains appears to be largely the Gulf of Mexico, although the tropical eastern Pacific also contributes.

Gulf of Mexico sea surface temperatures seem to vary less than those in the Gulf of California, Gutzler said. Meanwhile, eastern Pacific trends vary with El Niño fluctuations, which influence Arizona less consistently than Mexico, explained Wayne Higgins, a Climate Prediction Center researcher and leader of the

continued on page 22

Monsoon, continued

North American Monsoon Experiment. In general, El Niño tends to suppress monsoon activity, especially in Mexico, Higgins noted.

Now for the caveats: Some speculate El Niño events could increase as climate warms (although others suspect the opposite). Sea surface temperatures at a specific location also depend on ocean currents, which may change as climate changes. Along coastlines, upwelling of cooler water from below the surface potentially could temper some sea surface warming.

Even the relationship between tropical convection and sea surface temperatures of 26 degrees could change as the atmosphere warms. (For more on the latter, see the July 1, 2004, *Journal of Climate* paper by Chia Chou and J. David Neelin.) Gutzler noted that scientists still are working to unravel the physical reasons for the 26-degree-Celsius threshold for tropical convection.

"The fact that we see this threshold doesn't mean we understand it," he pointed out.

Land heating

Back in 1884, H.F. Blanford observed that the monsoon in India seemed to be weaker during years when there was abundant snow on the Tibetan Plateau (*Proceedings of the Royal Society of London*). His proposed mechanism—that heating the mountainous land pulls winds and rains landward—is still considered relevant.

Basically, the summer sun heats the land, causing air to rise. This creates a slight vacuum, compelling offshore air to rush in and fill it. The result is a landward shift in prevailing wind direction. As is often the case, with wind comes rain—especially when the wind is seaborne.

The connection between snow cover, and the cooling moisture it imparts, is not the only factor influencing monsoon dynamics, to be sure. But it's potentially important to pin down because most climatologists expect global warming to exacerbate the ongoing trend toward earlier western U.S. snowmelt documented by researcher Daniel Cayan and others (*Bulletin of the American Meteorological Society,* March 2001).

Arizona State University researcher Timothy Hawkins and colleagues found relatively low summer snow cover in the northwestern United States linked at the broad scale to higher summer rainfall in the Southwest. Similarly, University of New Mexico's Gutzler has found relatively low April snowpack in the Rocky Mountains tended to correlate with strong monsoon seasons in New Mexico, but less so for Arizona (*Journal of Climate,* November 15, 2000).

Even in New Mexico, the year-to-year variability was more predictable in some decades than others. Gutzler suspects the drought that began in the mid-1990s suppressed the relationship that held for the previous three decades, he explained in a follow-up telephone conversation earlier this month.

The potential for large-scale drought patterns to blur the relationship also adds uncertainty to predictions about what will happen to the monsoon with global warming. Some climatologists suspect western drought will become more frequent with global warming.

The investigation continues into how snowcover and drought factors relate to Southwest monsoon seasons, and whether the link involves land heating itself or the atmospheric processes that influence snow cover and drought variability.

Atmospheric moisture

A warmer atmosphere can hold more moisture, based on a physical relationship known as the Clausius-Clapeyron equation. This relationship is among the reasons given in an article by Kevin Trenberth and colleagues on how precipitation could be expected to increase and occur in more extreme events as climate warms (*Bulletin of the American Meteorological Society,* September 2003).

However, a projected increase in global precipitation does not necessarily translate into an increase in regional or local precipitation—especially effective precipitation, which is the moisture that remains to nourish plants and fill streams after evaporation has taken its toll.

First of all, the warming atmosphere's increasing ability to hold moisture means evaporation rates will climb. Rates could increase by about 5 percent for a rise of about 4 degrees Fahrenheit, based on calculations by Paul Brown of the Arizona Meteorological Network. So even with an increase in rainfall, there can be a drop in effective precipitation.

On top of that, atmospheric conditions vary daily, with dozens of interacting varieties possessing different modus operandi. Given the myriad of atmospheric combinations that contribute to climate variability, some areas and regions are sure to see a drop in effective precipitation, while other areas will get more than they can handle, at least at some scales.

So, will global warming strengthen the North American monsoon? It's not an open-and-shut case. But it doesn't take Sherlock Holmes to conclude that climate variability will continue to be an accomplice in any long-term changes in monsoon behavior related to global warming.

Next month's article will delve into some of the atmospheric processes affecting North American monsoon strength.

Melanie Lenart is a postdoctoral research associate with the Climate Assessment for the Southwest.

Inquiry into monsoon and global warming continues

Troublesome twist: Atmospheric variables make prediction tough for summer rain

by Melanie Lenart

Editor's Note:
This is the second in a two-part series about how the monsoon might change with global warming. This article focuses on some of the atmospheric influences on the North American monsoon. For last month's article visit http://www.ispe.arizona.edu/climas/forecasts/articles/monsoon_June2005.pdf.

Some circumstantial evidence points to the possibility that global warming will yield stronger monsoons. Increases in sea surface temperatures, land heating, and air temperatures suggest the potential for an increase in summer rainfall.

Mystery solved? Not quite. There's a plot twist: Atmospheric variability remains elusive when it comes to the North American monsoon, which funnels summer rainstorms into the Southwest. Because the description of atmospheric variability remains sketchy, climatologists are seeking more clues before they will guess how the monsoon will respond to climate change.

"There's not much out there in terms of climate change and the monsoon," noted Arizona State Climatologist Andrew Ellis, alluding to the scientific literature on the North American monsoon. "I don't think people have a great feel out there how (atmospheric) flow would be affected by climate change."

Figure 1. The U.S. region affected by monsoon is restricted to the Southwest. Graphic courtesy of Andrew Ellis.

The North American monsoon has remained unresponsive to warming—at least where it reaches into the southwestern United States (Figure 1). Ellis finds no evidence of a trend toward more rainfall during the southwestern U.S. monsoon season (Figure 2), even though the Earth's surface has been warming for many decades.

Lack of data complicates efforts to unravel the mystery behind North American Monsoon variability. In a way, the southwestern U.S. is akin to a mere bystander—the main monsoon action centers on Mexico's Sierra Madres. While reliable U.S. data describing atmospheric activity exists from about the mid-20th century, comparable data in Mexico remains sparse to this day.

Since early 2004, researchers with the North American Monsoon Experiment (NAME) have been launching weather balloons, analyzing data, and studying monsoonal thunderstorms in intensive bursts of coordinated activity in both Mexico and the Southwest, explained NAME project leader Wayne Higgins. The project runs through 2008.

Meanwhile, satellites help fill in some of the missing puzzle pieces, but they provide only a few decades of data—a short time frame compared to some of the decades-long fluctuations that can influence monsoon strength. Even U.S. climate station data is considered short by these standards.

Although climatologists traditionally turn to computer modeling for insight on future changes, the General Circulation Models (GCMs) used to represent global climate are not yet up to the challenge for the North American monsoon. "The current generation of models doesn't do a good job of representing the monsoon, for a whole variety of reasons," said Andrew Comrie, a Climate Assessment for the Southwest (CLIMAS) researcher. GCMs have trouble modeling clouds, convection, and precipitation in general, he noted, in addition to using a spatial scale with no relevance to the monsoon. "It's a recipe for not getting it right in the GCMs."

Thinking outside the box

From a process perspective, global warming may affect some of the underlying drivers of the monsoon—sea surface temperatures, land heating, and atmospheric moisture—as discussed last month. The circumstantial evidence regarding the response of these drivers to global warming suggests a strengthening of monsoons around the world.

Long-term records support such an interpretation, showing the Asian monsoon tended to strengthen during warm episodes of the past, and weaken during cool periods (For example, see *Nature*, January 23, 2003). On the other hand, the immense size and height of the Tibetan Plateau make the Asian monsoon somewhat more predictable than the North American monsoon.

The sheer number and inherent variability of the factors affecting the North American monsoon make climatologists leery of predicting how it will respond to global warming. Comrie rattled off half a dozen influences on the North American monsoon during a July 14 interview in Tucson, when residents were still waiting for this year's monsoon to begin. The list includes sea surface temperature and land heating, but also the influence of mid-latitude westerly wind patterns, tropical easterly trade winds, and global-scale descent of tropical air.

continued on page 24

Monsoon, continued

"They're all connected and it's all fluid, so it's not like you're moving cogs in a machine. There are just too many feedbacks," Comrie said. "It may be that there will be a dramatic change in one of these that overrides everything else. We don't know."

Changes in El Niño regimes could impact the monsoon, for instance. El Niño tends to suppress monsoon strength in Mexico, Higgins said. El Niño's dampening of Arizona's monsoon season is less noticeable but still detectable statistically, noted Klaus Wolter, a meteorologist with the Climate Diagnostics Center in Boulder.

Still, the El Niño advantage in making skillful predictions of winter precipitation falls short when it comes to forecasts of summer rainfall, at least for the U.S. Southwest. What's more, climatologists are still debating how global warming might affect El Niño regimes.

Too many leads to follow

Predicting monsoon behavior on a seasonal scale poses a major challenge to climatologists, although experimental predictions by both Wolter and Ellis for a relatively dry season in Arizona this year seem to be panning out.

True, it's almost certain the seasonal cycle will kick in at some point with its accompanying thunderstorms. But rainfall rates fluctuate widely from year to year. In the southwestern U.S. dataset compiled by Ellis (Figure 2), average monsoon-season rainfall ranged from about 3 inches (8.3 cm) in 1975 to more than 9 inches (23.8 cm) in 1990.

Further, within that region, the distribution of rainfall typically ranges from abundant to sparse in the same year. In particular, New Mexico and Arizona often seem to follow different leads.

Tropical dynamics

Suspects in the investigation include anything that might influence the position of the signature monsoon "anticyclone" (Figure 3), including the climate features on Comrie's list of factors affecting monsoon variability. Year-to-year variability in southwestern summer rainfall relates in large part to the location and size of this anticyclone.

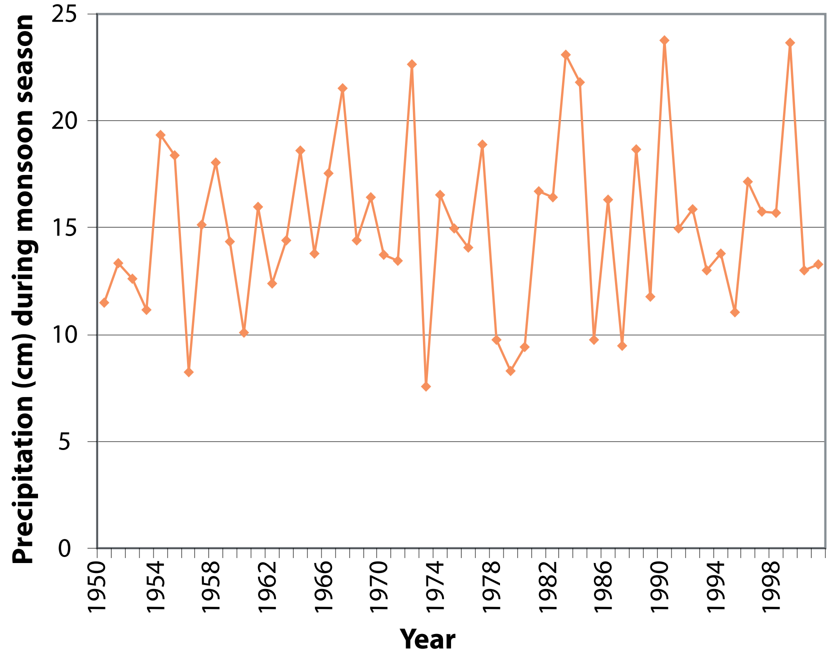


Figure 2. Annual precipitation in the monsoon region during the monsoon season fluctuates widely by year, but the fluctuations show no ongoing trend toward an increase in seasonal rainfall in recent years. Graphic based on 1950–2001 dataset accessible from Andrew Ellis' website at http://geography.asu.edu/azclimate/monsdat.htm.

The anticyclone itself goes by a variety of aliases, including the Four Corners High. The high-pressure anticyclone is easier to define on weather maps (Figure 3), but its presence means a surface low exists below. The combination of a surface low and an upper-level high defines monsoon circulation.

These terms relate to how air flows in the atmosphere. Air may be invisible like a gas, but it flows in currents and moves in waves like fluid. While water will flow from mountaintop ridges to the low-lying valleys on the landscape, air will flow from areas of high pressure—often called atmospheric ridges—to "troughs" of low-pressure.

Surface lows allow moisture to rise more freely in the atmosphere, increasing their odds of forming the towering thunderclouds that can reach into the cooler heights needed to produce rainfall. Meanwhile, the descending air that characterizes highs generally limits precipitation.

At the global scale, heated air rises in the equatorial region and nearby tropics that take the brunt of the sun's incoming punch. The rising air loses steam and begins to descend by the time it reaches the subtropics—and to dry out as it warms on its way down, as descending air does. Climatologists call these global-scale ups and downs Hadley cell circulation.

This circulation pattern helps imprison the subtropics in dryness, as Hadley cell highs tend to suppress precipitation. It's no coincidence that the world's deserts—including the Southwest's Sonoran Desert—tend to be located in the subtropics, centered at around 30 degrees latitude North and South.

Those clear skies that distinguish the subtropics can cloud up during the

continued on page 25

Monsoon, continued

monsoon season, though. In monsoon circulation, subtropical surface air "balloons" up into higher reaches, mimicking the tropic's usual approach to promoting convective activity such as thunderstorms, Ellis explained.

"It just opens the door for some very light flow and accompanying moisture from the south," he added. As discussed last month, moist air tends to rush in from the Gulf of California to Arizona, and from the Gulf of Mexico to New Mexico.

Wrong side of the storm tracks
When mid-latitude weather patterns reign, as often happens during El Niño years, westerly winds can delay the dynamics that usher in the monsoon.

Going back to the water analogy, the westerlies act as a river of airflow that speed along several miles above the Earth's surface. The jet stream speeds along in their core, like swift-flowing water in the center of the river. Sometimes the westerlies follow a straight course, staying mostly in line from west to east. Other times they can meander from Alaska down to Arizona, trailing cool air in their wake.

Although refreshing in the short term, the latter pattern restricts the formation of the anticyclone. Basically, it takes the stifle out of the summer heat needed to draw in warm, moist air from the south.

"That is a really killer for the monsoon," Ellis said.

The absence of sweltering stillness may be welcome by humans and other life forms—until the lack of seasonal relief from the monsoons creates its own problems. The July fire that raged through Tucson's Santa Rita Mountains is one example of how society pays for a sputtering monsoon that doesn't quite catch. Hundreds of hotshot firefighters battled the blaze, mostly in vain, at high personal and financial cost. Meanwhile, air quality in the greater Tucson area also suffered during the event.

When westerly winds shift north, or surface heating manages to override their interference, the anticyclone can take shape. Although the anticyclone brings rainfall to those under its domain, its presence often signifies dry spells for those outside its province, especially the areas falling north and east of its sway.

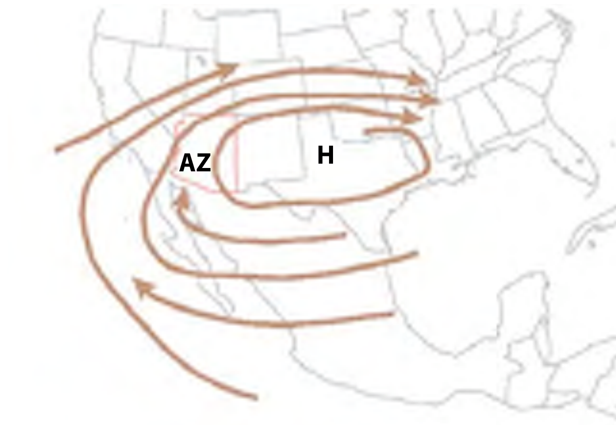


Figure 3. The air circulation patterns at 18,000 feet show the signature "anticyclone" that helps define the North American monsoon. Graphic courtesy of the National Weather Service, http://www.wrh.noaa.gov/twc/monsoon/mexmonsoon.php

"That monsoon anticyclone is huge, and it tends to suppress precipitation in the Great Plains," explained Higgins, whose October 1997, *Journal of Climate* research paper with colleagues first documented the see-saw action between the Southwest and Great Plains rainfall.

For the 30 years of data they averaged, the southwestern U.S. increase in rainfall coincided with a decline in summer rainfall in the Great Plains area between about 105 degrees and 85 degrees West. Monsoon circulation puts the Great Plains in the path of air descending from the heights of the anticyclone, creating a high pressure zone of dry air at the Earth's surface.

The correlation between summer rainfall in the Southwest vs. the Great Plains seems to indicate that stronger monsoon seasons do not represent an increase in overall U.S. rainfall, but merely a redistribution of regional rainfall. So it seems likely that whichever way the wind blows in a climate change scenario, some region of the country will suffer from a lack of moisture.

No solution in sight
Just how will the North American monsoon fare with global warming? It seems this case will be relegated among the great unsolved mysteries until more clues turn up to produce a coherent explanation for year-to-year monsoon variability.

Although global warming seems destined to affect some of the drivers influencing monsoons around the world, such as warming of land and sea, the atmospheric response to these drivers remains unclear when it comes down to considering the regional scale of the Southwest.

At this point, the plentiful cast of characters exerting influence on the monsoon and its characteristic anticyclone resembles the early stages of a game of Clue, when half a dozen or more suspects could be the culprit. Unlike this form of child's play, the real-world solution will probably involve a host of influences working together in a complex scheme that defies detection for many years, perhaps even decades.

One thing's certain: It will take continued dedicated effort by the many investigators now working diligently to solve the mystery. Until they do, the solution remains up in the air.

Melanie Lenart is a postdoctoral research associate with the Climate Assessment for the Southwest.

Hurricane intensity rises with sea temperatures

Some variations linked to warming air temperatures

By Melanie Lenart

High sea surface temperatures fuel stronger hurricanes.

No one argued about that at a recent workshop on tropical cyclones and climate held at the International Research Institute for Climate Prediction in New York. The distinguished experts at the March workshop even agreed that Atlantic hurricane seasons are likely to remain active for several more decades.

But what is driving the rise in sea surface temperatures (SSTs) so strongly linked to hurricane activity—global warming or natural variability? And how might other factors influence hurricane activity as the world warms? That was up for debate.

The answers have important implications for society. If hurricanes and other tropical cyclones are drawing their extra strength from global warming, then the world can expect to face a century or more of intense hurricanes For the landlocked Southwest, storms that start out as tropical cyclones can provide welcome rains and the occasional flood.

If the observed increase in hurricane intensity relates only to naturally recurring fluctuations, residents along the South and East coasts menaced by Atlantic hurricanes could expect a reprieve within a few decades. The East Pacific hurricane seasons that moisten the Southwest, meanwhile, could slow down in the near future, based on previous experience. A busier-than-average Atlantic season often means a calmer-than-usual East Pacific season, which many attribute to the influence of El Niño.

The power behind North Atlantic and North Pacific seasonal hurricanes combined has more than doubled since about the mid-1970s, as shown by research by Kerry Emanuel of the Massachusetts Institute of Technology (*Nature*, August 4, 2005). Reliable records go back to the 1940s. The power dissipation index (PDI) he used tallies tropical cyclones of any strength and includes their size and life span when considering how much energy they contained.

SSTs explained about 88 percent of the variability in Atlantic seasonal hurricane energy since 1970 when compared in multi-year trends, Emanuel noted during the workshop. As ocean temperatures rise, so does hurricane intensity (Figure 1).

Ocean temperatures have been rising around the world, most notably since the mid-1990s, as documented by Sydney Levitus and colleagues at the National Oceanographic Data Center (*Science*, March 24, 2000). The scientific community agrees that rising temperatures in the ocean and air relate to global warming from society's use of fossil fuels like coal, oil, and gas.

Emanuel showed evidence that Atlantic SSTs generally move in synch with northern hemisphere air temperatures when considered at the decadal scale (Figure 2). His results challenge the existence of the Atlantic Multidecadal Oscillation, a mode of natural variability in SSTs that was originally proposed by Michael Mann, Emanuel's co-author in the new study (*Eos*, June 13, 2006).

"I would submit to you that there's just no plain evidence now that you have an oscillation," Emanuel said. "There just isn't evidence in nature, as opposed to models, for this."

These findings imply that Atlantic SST will continue to increase with warming air temperatures, strengthening hurricanes at least to some degree as it does. Northern hemisphere temperatures are projected to rise by another 3 to 10 degrees Fahrenheit (F) throughout the twenty-first century.

Those arguing that natural variability, not global warming, is driving SST increases and other factors that influence hurricane strength include Christopher Landsea of the Hurricane Research Division. His paper with lead author Stanley Goldenberg, Alberto Mestas-Nuñez, and William Gray maintains that hurricane activity reflects a pattern of ups and downs that stay in place for decades at a time (*Science*, July 20, 2001).

"With Kerry's very interesting results today, I don't know if I'd say it's a cycle or not, but there is multi-decadal variability," Landsea said at the workshop, referring to Emanuel's work pairing air temperature with SST (Figure 2).

Landsea and Emanuel have been facing off on whether the increase in intense hurricanes stems from natural variability or global warming in a variety of venues, including a May media briefing and the pages of scientific journals (e.g., *Nature*, December 22, 2005).

Landsea argues that researchers have gotten better at detecting hurricanes in recent years, making it challenging to compare recent tallies with earlier ones. Even the Atlantic dataset, considered the world's best from about the mid-1940s, contains potential wind speed biases, he said. Meanwhile, he has little faith in the data used to assess global increases in cyclone strength, such as that used in the analysis by Peter Webster of the Georgia Institute of Technology and several colleagues that made headlines in 2005.

Webster and the others compared cyclone records derived from satellite images for six ocean basins around the world for 1975 through 2004. They found the number of intense storms

continued on page 27

Hurricanes, continued

had increased by 57 percent when they compared the second half of the record to the first half (*Science*, September 16, 2005). For these purposes, intense hurricanes refer to Category 4 and 5 cyclones, which have sustained wind speeds above 130 miles per hour.

SST had increased during the second half of the record as well, the authors noted. Their analysis of the East Pacific basin showed the number of intense hurricanes jumped from 36 in the first period (1975–1989) to 49 in the second period (1990–2004), even though the total number of hurricanes remained about the same for the two time frames.

The satellite measurements use factors such as eye definition and apparent cloud height to estimate cyclonic wind speeds. Landsea suggested the data may contain flaws because the measurements come from a variety of people who made their assessments during the year in question. Since the earlier time period, satellite coverage, hurricane recognition, and technology all have improved. The researcher said when he and a colleague applied modern detection techniques to satellite images from the earlier period for the Indian Ocean, they found several intense hurricanes that had not been included in the dataset used by Webster and others.

Webster, in turn, pointed to a recent reanalysis of the South Indian Ocean—the region where data presented the most problems—which reached similar results as their 2005 paper. The random errors canceled each other out in the end, he said, leading to the result that the Indian Ocean has seen an increase in intense hurricanes like the other five basins.

Other researchers are finding similar results from an independent data set that does not involve satellite images, Webster added. He pointed to a paper published earlier this month by Ryan Sriver and Matthew Huber of Purdue University (*Geophysical Research Letters*, June 2006).

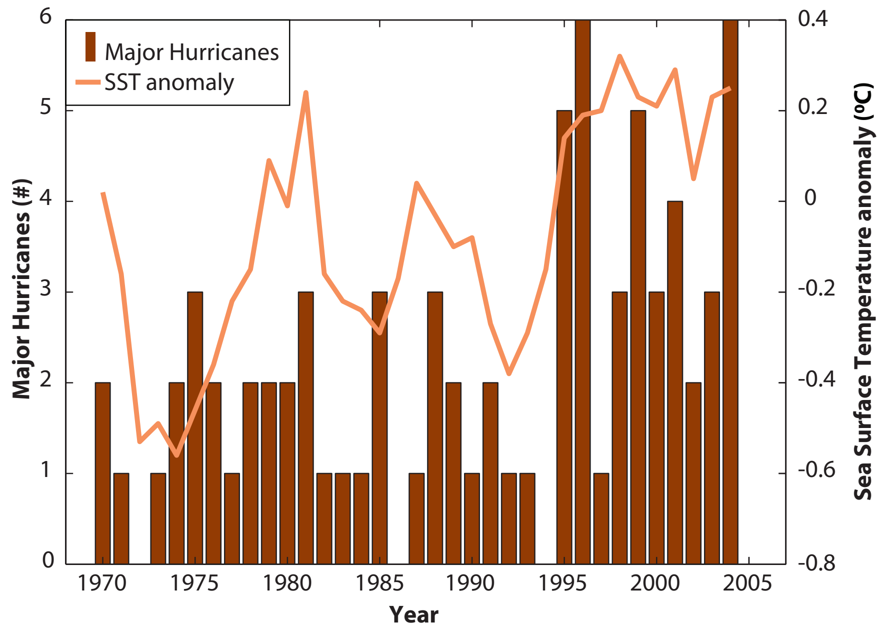


Figure 1. The number of major hurricanes a year in the northern Atlantic (bars) tends to reflect sea surface temperatures (SSTs) fluctuations (line). Major hurricanes have sustained winds above 110 miles per hour. Data courtesy of Christopher Landsea of the National Hurricane Center.

The researchers used data for 1958–2001 developed by a European weather forecasting center to calculate the power dissipated by hurricanes and other tropical cyclones around the world. When comparing the pre-1979 data to the later part of the record, they found the overall PDI had increased by about a quarter. The Purdue researchers' results for the globe looked almost identical to Emanuel's results, even though they used a different approach to average out annual variability, and they considered the world rather than just the northern Atlantic and Pacific. The results also support Webster's results, as the authors note.

A global assessment using hurricane tracking data found only a small increase in intense hurricanes when splitting the last 20 years of data into two halves for comparison (*Geophysical Research Letters*, May 2006). By this assessment, global activity peaked between 1992 and 1998, a time frame that was split by the comparison of 1986–1995 to 1996–2005.

Researchers on both sides of the argument are puzzled by the extent of the apparent hurricane response to a relatively minor rise in SST. SSTs have risen by only about half a degree F on average globally, and slightly less than 1 degree F in the Atlantic region where hurricanes tend to develop.

Yet the average annual number of major hurricanes per year in the Atlantic more than doubled when comparing the 1995–2004 to the period 1971–1994, based on data from Landsea (Figure 1).

During the earlier time frame, Atlantic SSTs averaged below 83 degrees F during the peak hurricane season (August–October) in all but three years. Since 1995, Atlantic seasonal mean SST has averaged above 83 degrees—but the difference between the two averages represents only about 1 degree F.

"The sensitivity is a lot more than we would have predicted," Emanuel said, referring to his Atlantic research that showed a similar jump in intense hurricanes. The combined measure of

continued on page 28

Hurricanes, continued

hurricane power increased roughly four times more than his earlier models had projected it would based on the seasonal SST rise, he indicated. While his model suggested a 5 percent increase in peak winds with a 1 degree Celsius (C) warming, his analysis showed a 10 percent increase in peak winds with little more than half a degree C warming.

Emanuel suggested that the lack of major volcanic activity since Mount Pinatubo's eruption in 1991 could be affecting relevant dynamics of the upper atmosphere as well as SSTs. Volcanic eruptions can temper the warming for a year or so when their explosions spew aerosol particles up into the stratosphere. Pollution involving sulfate aerosols can have a similar temporary cooling effect. In fact, he suspects aerosols from pollution and volcanoes may have been behind the Atlantic's calm phase from the mid-1970s through the mid-1990s.

Vertical wind shear also has an important influence on individual storms, Emanuel noted, even though it doesn't show up as important in "smoothed" data in which values for several consecutive years are averaged together. Wind shear occurs when high-level winds move much faster or in a different direction than those at the surface. Hurricanes tend to form and persist more frequently in situations of low vertical wind shear.

Landsea agreed wind shear wielded an important influence on individual storms. "Most of the time, hurricanes are like people. They don't live up to anywhere near their potential. And most of the time it's because of wind shear," he said.

At the seasonal scale, vertical wind shear tends to decrease as SSTs increase, as Goldenberg and Landsea and their co-authors note in their 2001 paper.

Scientists have long known that SSTs must reach about 80 degrees F before hurricanes can form. In the current climate, this temperature seems to serve as a general threshold for tropical convection—the process behind hurricanes, monsoons, and even many thunderstorms.

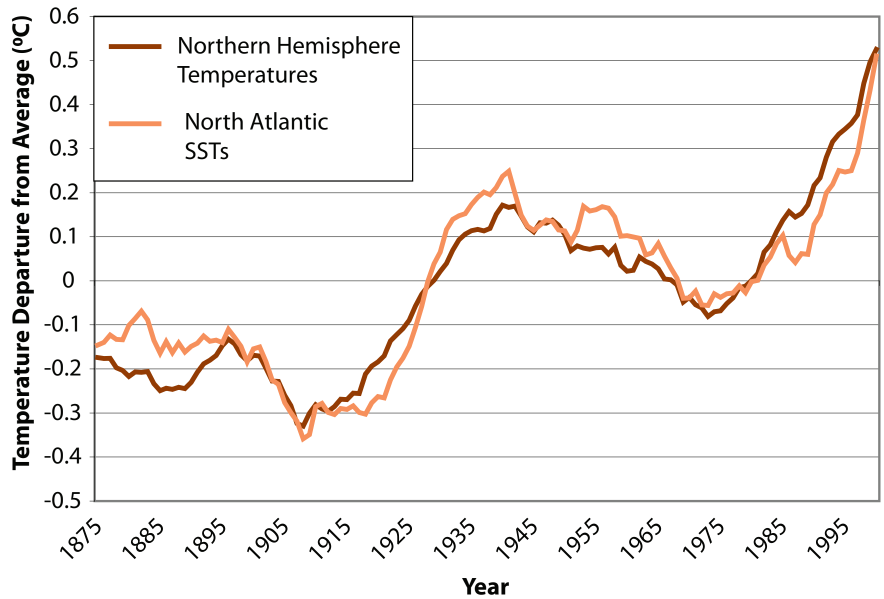


Figure 2. North Atlantic sea surface temperatures (SSTs) tend to closely match northern hemisphere air temperatures when both are smoothed at the decadal scale. In both cases, temperature values cover the peak hurricane season of August-October. Data courtesy of Kerry Emanuel of the Massachusetts Institute of Technology.

For instance, David Mitchell's research on the North America's monsoon system has found Arizona's summer monsoon rains won't begin until its moisture source, the Gulf of California, reaches close to 80 degrees Fahrenheit at the surface (*Journal of Climate*, September 1, 2002). Similarly, Chidong Zhang's research links this temperature threshold to the tropical convection behind many thunderstorms (*Journal of Climate*, October 1993).

What's more, Mitchell has found that the Gulf's SST must top 84 degrees to trigger the heavy rains that mark a strong monsoon in Arizona. Increases beyond that temperature don't have as dramatic of an impact, he indicated.

If a similar threshold applied to hurricane activity, that could help explain the sudden jump in intense Atlantic hurricanes from a relatively small change in temperature (Figure 1).

A threshold scenario would imply some good news: It could mean society is not necessarily facing a doubling in intense hurricane numbers for every rise of 1 degree Fahrenheit. On the other hand, it could imply that intense hurricanes will continue to thrive unless ocean basins drop below the threshold temperature.

In a warming world, even the threshold temperature for spawning hurricanes can shift. The SST needed to launch tropical convection rises with global air temperature, Emanuel said. This further complicates the issue.

Given the impact of hurricanes on society, this topic will continue to generate debate until the scientists involved reconcile their results with their models and each other. But it's worth remembering that nobody is predicting a decrease in Atlantic hurricane activity anytime soon.

Melanie Lenart is a postdoctoral research associate with the Climate Assessment for the Southwest (CLIMAS). The SWCO feature article archive can be accessed at the following link: http://www.ispe.arizona.edu/climas/forecasts/swarticles.html

East Pacific hurricanes bring rain to Southwest

By Melanie Lenart

Pacific hurricanes and tropical cyclones can have a profound influence even on the landlocked Southwest—and, arguably, their impact may increase as the oceans warm.

"It turns out that there's quite a lot of tropical cyclone activity that actually impacts the Southwest," explained Elizabeth Ritchie, a climatologist who joined The University of Arizona faculty this summer. September is the peak month for this activity, which has resulted in some serious floods in years past.

An average of 2.2 remnants from East Pacific hurricanes and named tropical cyclones ventured into the Southwest each year between 1992 and 2004, representing 15 percent of the region's named storms, Ritchie found in an analysis she conducted with a colleague. A tropical cyclone must reach sustained wind speeds of 39 miles per hour (mph) to qualify for a name, and 74 mph to attain hurricane status.

All but two of the 29 cyclones brought at least some rain to the Southwest. The researchers defined the Southwest as Arizona, California, and New Mexico.

"The main story is Albuquerque really does the best out of all these sites," Ritchie noted, adding, "Tucson is not far behind."

During this 13-year time frame, Albuquerque received a total of 20 inches of rainfall from tropical cyclone remnants, while Tucson received 12 inches and Phoenix collected 4 inches. Compared to the annual average rainfalls for these three cities, the values amount to half a year's worth for Phoenix, a year's worth for Tucson, and more than two years' worth for Albuquerque.

About 1.3 tropical cyclone remnants affected the Southwest each year during the time frame 1966–1984, according to an earlier analysis by Walter Smith of the National Oceanic and Atmospheric Administration (NOAA) that was published in 1986 as a NOAA Technical Memorandum.

However, it's unlikely the studies by Ritchie and Walter are directly comparable. Detecting remnants of tropical cyclones remains more of an art than a science, researchers noted, as official long-term tracking data ends when wind speeds fall below tropical storm status.

From 1974 through 2004, the number of intense East Pacific hurricanes increased by about a third, according to a study by Peter Webster of the Georgia Institute of Technology and several colleagues. Intense hurricanes have sustained winds above 130 mph. Webster and his colleagues compared data based on satellite imagery and found 49 intense hurricanes forming from 1990 through 2004 compared to 36 forming from 1974 through 1989.

Their finding and its perceived link to global warming via rising sea surface temperatures remains controversial among some researchers (see June 2006 *Southwest Climate Outlook*). Although climate experts agree rising ocean temperatures strengthen individual hurricanes, they disagree on whether past data is reliable enough to reveal a trend directly connected to global warming.

More intense East Pacific hurricanes won't directly translate into more rainfall in the Southwest, at any rate, as David Gutzler, a climatologist at the University of New Mexico, pointed out. That's because storms are more likely to become intense when contacting the warm waters of the open sea, he noted, while those heading into the Southwest must swing toward cooler coastal waters. The current from Alaska typically keeps U.S. coastal sea surface temperatures in the 70s and below even in August.

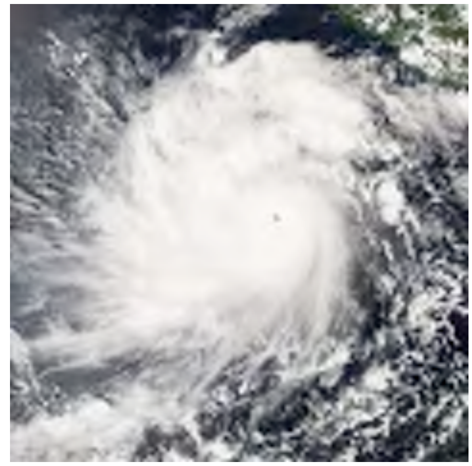


Figure 5. Satellite image of hurricane Javier on September 13, 2004 approximately 610 miles southeast of Cabo San Lucas, Mexico. Source: Jesse Allen, NASA Earth Observatory, data from the MODIS Rapid Response team

Tropical storms generally must encounter sea surface temperatures (SSTs) of 83 degrees Fahrenheit or more to attain the sustained 111 mph wind speeds of major hurricanes, based on a study of 270 Atlantic hurricanes and corresponding SSTs by Patrick Michaels and colleagues from the University of Virginia (*Geophysical Research Letters*, May 2006).

The tropical storms that do reach the Southwest can provide drought relief or cause floods, sometimes both. The remnants of Hurricane Javier (Figure 5) helped break a string of dry years in September 2004, ushering in a wet winter by gently soaking parts of drought-parched Arizona and New Mexico.

Too much of a good thing led to flooding in the autumn of 1983, when four cyclone remnants visited the Southwest. The storm from former Hurricane Octave created the most havoc, causing $500 million in flooding damage to Arizona with its days-long rains.

Melanie Lenart is a postdoctoral research associate with the Climate Assessment for the Southwest (CLIMAS). The SWCO feature article archive can be accessed at the following link: http://www.ispe.arizona.edu/climas/forecasts/swarticles.html

Water Resources

Water Resources Foreword
By Bonnie Colby

As the earlier section of this book emphasizes, the southwestern Unites States faces significant changes in temperature and in precipitation patterns due to climate change. Such changes will inevitably strain the already precarious balance between water supply and demand. Water managers, users and other stakeholders face an immense array of challenges, all likely to be affected by projected changes in the regional climate.

First consider the competing demands in the region. Agriculture is the largest water user in the U.S. Southwest, accounting for more than 80 percent of consumptive use. Agricultural water demand will shift as temperature regimes become warmer. There will be increased evaporation from agricultural conveyance canals and farm fields and crop consumptive use per irrigated acre will be higher with higher temperatures. Moreover, cropping patterns are likely to shift as climate change affects crop yields and profitability.

Residential water demand is growing with the growth in regional population, and water consumption by landscape and turf is likely to increase with higher temperatures. Landscape preferences and choices between turf and low water use plants may shift in ways we cannot predict in response to changing temperatures. Outdoor water demand is an important component of overall municipal demand in the Southwest, and requires water in the hot dry periods when agricultural water demand also is at its peak.

The growing population of the region demands water for recreation in a variety of forms. Water-based recreation on reservoirs and rivers is an important part of the Southwest lifestyle and fuels many local economies, as do winter sports that rely upon snow pack. As competition for water increases and snow pack decreases in the face of climate change, those local economies that rely upon water-dependent recreation are going to be stressed.

Moreover, endangered fish recovery programs and surface water quality programs rely upon water remaining in streams and rivers – something that will be more difficult to assure in the future. Balancing urban, recreational, environmental and agricultural demand will become more of a challenge given predicted changed in the climate of the Southwest.

As the chapters in this section emphasize, water stakeholders and policymakers are beginning to grapple with the implications of climate change for water management. Shortage-sharing meetings and negotiations occur regularly amongst the seven states of the Colorado basin, federal agencies, tribal governments, environmental NGOs, irrigation districts and cities. Preparing for climate change involves examining the weak links in existing water management and law, such as Arizona's

continued on page 32

continued

failure to link groundwater use and surface water impacts in its water law framework. Innovations such as water banking and dry year agricultural forbearance agreements are already occurring and likely to receive new impetus as climate change progresses.

The complex interrelationships between water management and regional energy supply and demand are receiving more attention so that the region can be better prepared for the accumulating effects of changes in temperature, snowpack and seasonal precipitation patterns. The articles presented in the following sections represent the type of cutting-edge inquiries driven by stakeholder needs that will help the region's water managers and water users respond to the challenges ahead.

Bonnie Colby is a University of Arizona professor in Agricultural and Resource Economics and Hydrology and Water Resources. She is an investigator with the Climate Assessment of the Southwest project within the university's Institute for the Study of Planet Earth. Her specialties include the economics of water-rights negotiations and transactions, dry-year reliability and water policy.

Low flow in the Colorado River Basin spurs water shortage discussion among seven states

by Melanie Lenart

The reservoirs in the Colorado River system provide a cushion in times of trouble, much like money in the bank. But about half of the rainy day water savings have been spent during the past five years of drought, spurring water managers in Arizona and New Mexico and the five other states that depend on the Colorado to seriously discuss how they might share a potential shortage.

The main issue of contention is that Glen Canyon Power will be unable to produce electricity by 2007 if the drought continues unabated and no changes are made in management decisions. At full capacity, the company uses Lake Powell to generate enough electricity to power about 1.5 million homes, including users in Arizona and New Mexico.

“We don’t know if this is a 5-year drought or the fifth year of a 15-year drought,” explained Robert Johnson, regional director of the Lower Colorado Region for the U.S. Bureau of Reclamation (USBR), which tracks and distributes Colorado River water. “From a management perspective, we’ve got to hope for the best and plan for the worst.”

Johnson displayed his optimism during a recent talk at the University of Arizona’s Water Resources Research Center. He noted that the reservoirs can store about 60 million acre-feet, about four times the Colorado’s annual average streamflow, mainly in Lake Powell and Lake Mead. Both lie along Arizona’s borders.

“What that means is we’ve got the ability to weather drought. In fact, we have weathered drought—we’ve had five years of drought and the reservoirs are still half full,” he told the group.

At the end of October, Lake Powell was filled to 38 percent of its capacity, while Lake Mead was registering 54 percent of its capacity. However, USBR numbers indicate only about 12 million acre-feet could be jointly withdrawn from the two reservoirs before power production ceased completely, assuming no changes to the generating system and no additional water deposits beyond that for downstream use.

Timothy Henley, manager of the Arizona Water Banking Authority, found some reason for hope in that historic droughts affecting the Colorado River basin tend to last four to six years (see Table 1), based on instrumental records of streamflow since 1906. In October, storm fronts, including in northwestern Arizona, finally broke the nearly five-year streak of below-average monthly precipitation tallies that the Bureau of Land Management had been reporting for the watersheds feeding the Colorado River as a whole.

Colorado River flow throughout the system averaged 9.9 million acre-feet a year since 2000, which puts average river flow during this 5-year period even lower then during the 1950s drought and others of similar 4- to 6-year time spans (Table 1). Meanwhile, the seven western U.S. states and two Mexican states using Colorado River water consume about 96 percent of the annual average river flow. An acre-foot is roughly 326,000 gallons of water, enough to supply an average family of four for a year.

There have been media reports that Lake Mead, in particular, might never refill even if streamflow returned to its “average” of 15.1 million acre-feet a year, an estimate based on measurements since 1906. In the next couple of decades, basinwide water consumption is expected to grow with the population of the Upper Basin states to reach the allocated 16.5 million acre-feet from its current 14.5 million acre-feet a year (Table 2).

However, as a USBR slide show reminded, “we never get average hydrology.” The estimated natural flow of the Colorado River registers as a series of ups and downs that ranged from about 5 million acre-feet in 1977 to more than 24 million acre-feet in both the 1983 and 1984 calendar years, based on measurements at Lee’s Ferry in Arizona (Figure 1).

continued on page 34

Table 1. Average flow during the current drought (top row) was lower than during any other drought in the instrumental record.

Time frame	Duration	Average Annual Flow (in acre-feet)
2000–2004	5 years	9,900,000*
1953–1956	4 years	10,200,000
1988–1992	5 years	10,900,000
1959–1964	6 years	11,400,000
1931–1935	5 years	11,400,000

Source: U.S. Bureau of Reclamation.
*Preliminary estimate.

Table 2. The Colorado River is overallocated even when the period of flow attains its natural flow average of 15.1 million acre-feet a year. However, the Upper Basin states are not using all of their allocations at this point in time.

Political Entity	Annual allocation (in acre-feet)
Upper Basin States	7,500,000*
Colorado	3,900,000*
New Mexico	800,000*
Utah	1,700,000*
Wyoming	1,000,000*
Lower Basin States	7,500,000
California	4,400,000
Arizona	2,800,000
Nevada	300,000
Mexico	1,500,000
Total	16,500,000

Source: U.S. Bureau of Reclamation.
* The Upper Basin states use a percentage formula rather than acre-feet to divide its allocation, which is why these rounded-off numbers do not tally 7.5 million acre-feet. Also, New Mexico’s share comes from a Colorado tributary, the San Juan River.

Low Flow, continued

"Between 1983 and 1986, we spilled about 45 million acre-feet of water to Mexico. If you see events like that, the reservoirs are going to fill," Henley said.

Henley, one of two Arizona representatives in ongoing discussions among the seven U.S. states vying for Colorado River water in these days of pending shortage, reported ongoing progress on interstate discussions during a November 9 public meeting at the Arizona Department of Water Resources' (ADWR) headquarters in Phoenix. The interstate group is essentially hoping to buy time, working out interim agreements on how to share the shortage in the hopes that the river hydrology will shift into a more plentiful mode before they have to seriously weigh whether to short Arizona users or lose power.

If an official shortage were declared in the Lower Basin, non-Indian agricultural users of Central Arizona Project (CAP) water—the 336-mile long system of aqueducts that delivers 1.8 million acre-feet a year to Maricopa, Pinal, and Pima counties—legally would take the first cut. About 80 percent of Arizona's share of the Colorado River goes to agriculture.

ADWR Director Herb Guenther reminded the approximately 75 people attending the Phoenix meeting that long-term records based on tree rings and isotopes indicate modern records might give an exaggerated version of "normal" streamflow.

"We're concerned that we're returning to a more 'normal' mode, rather than a 'shortage' mode," Guenther said, alluding to the evidence that the Colorado has been running high for most of the instrumental record when compared to the longer records of past climate.

Tree-ring records also reveal evidence of infrequent but severe droughts that span decades, which climatologists call

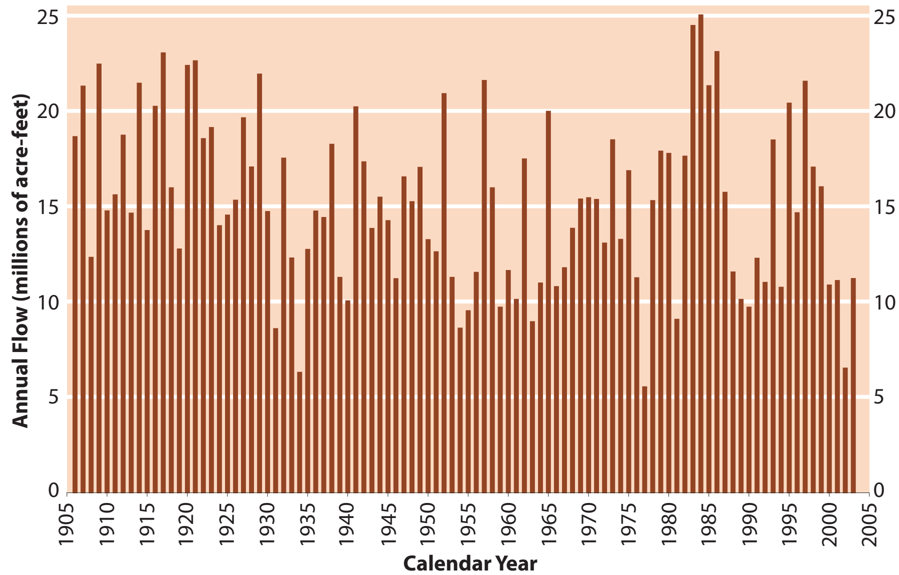


Figure 1. Estimates of Colorado River flow from 1906–2003 show that river levels fluctuate extensively around the average flow of 15.1 million acre-feet a year. The estimates are for flow throughout Colorado River's 246,000-square mile basin and were reconstructed by the U.S. Bureau of Reclamation based on gauged flow at Lee's Ferry in Arizona.

"megadroughts." Previous megadroughts, such as one in 16th century North America, wreaked havoc on local populations. However, even during a drought or megadrought, individual years of above-average streamflow can occur.

In fact, some note that the 1957 strong El Niño event that helped boost Colorado River streamflow to about 22 million acre-feet that year could be seen as an unusually wet year during a drought that actually stretched from 1953–1964. (See Table 1 and Figure 1 for illustration.)

However, even a couple of wet years like 1957 and 1958 within a stretch of dry years would do little to alleviate potential problems from the current drought, as researchers discovered when they modeled a long-term drought by adding the streamflow values for 1953–1964 to the current record.

Although the Lower Basin states theoretically could receive their full annual allocation during such a scenario, it would come at the cost of Glen Canyon hydropower. In the modeled "worst-case" scenario, Lake Powell's levels would be too low to yield electrical power for 10 of the next 17 years, as Don Ostler of the Upper Colorado River Commission summarized in a report available on the website for the ongoing Arizona Colorado River Shortage Workshops (http://www.awba.state.az.us/annc/AZ_CO_river_shortages.htm).

"Lake Powell takes most of the swings of the drought," as the USBR's Johnson noted. Lake Powell serves as the collection site for annual contribution from the Upper Basin states—New Mexico, Colorado, Utah and Wyoming—to the Lower Basin states of Arizona, California and Nevada.

After generating power through Powell's Glen Canyon dam, the water is channeled to the slightly larger Lake Mead. Glen Canyon Dam's power intake pipes are higher than the pipes that can supply water to the Lower Basin. As it is, electricity production is down to about 900 megawatts from its potential capacity of 1300, in part because the lower reservoir level means incoming water exerts less force on the turbines that generate power, explained Leslie James, executive director of the Colorado River Energy Distributors Association.

If push comes to shove, providing water to the agricultural users takes priority

continued on page 35

Low Flow, continued

over providing power, according to one of the many legal agreements guiding Colorado River use. Also, legal agreements have been interpreted as requiring the Upper Basin states, which produce about 90 percent of the runoff that feeds the Colorado River, to pass along the water allocated to the Lower Basin states even if it means shorting its own users.

The Lower Basin states have always received at least the full 7.5 million acre-feet allocated to them, Johnson noted, plus half of the 1.5 million acre-feet promised to Mexico as part of a 1944 treaty. But now some Upper Basin state managers are challenging the need to deliver the usual 7.5 million acre-feet a year—pointing out that legally they must deliver 75 million acre-feet every decade—and arguing that Lower Basin tributaries should contribute to Mexico's share.

One potential bargaining chip held by the Upper Basin is that a shortage of power would hurt the Lower Basin states as well, beyond increasing the cost of electricity to those who normally depend upon Glen Canyon Power sources. The utility provides about three-quarters of the $130 million Basin Fund revenues, some of which goes to protect endangered species, according to Ostler's report. So Arizona and New Mexico have more than a passing interest in reaching an interim agreement with the Upper Basin to avoid the need for official, and therefore heavily regulated, action.

Additional coverage of Colorado River Basin issues can be found in other University of Arizona publications, including Arizona Water Resource, available at http://www.ag.arizona.edu/AZWATER/awr/awrmain.html, and Southwest Hydrology, at http://www.swhydro.arizona.edu/.

Melanie Lenart is a post-doctoral research associate with the Climate Assessment for the Southwest.

Water managers share a range of viewpoints on the outlook for Colorado River water supplies

by Holly Hartmann

Do forecasts of El Niño, winter temperatures and precipitation, snowfall, and water supplies bode well for water managers in the Southwest? As with so many things in life, it depends on your perspective. A variety of viewpoints about future Colorado River Basin water supplies were in evidence at a recent interagency briefing held November 9 in Salt Lake City.

According to Tim Ryan, of the Bureau of Reclamation, Lake Powell and Lake Mead were at only 38 percent and 54 percent of 'live capacity' as of November 7, 2004. Lake Powell hasn't been this low since 1970, 6 years into the 16 years required for the reservoir to fill after completion of Glen Canyon Dam.

The Bureau sees the low levels as indicating successful water management, because the system was designed to have low water levels during times of drought. And there is no question the basin is experiencing drought. The 2000–2004 period has been the worst mid-range drought in historical records. Lake Powell had no above-average flows since September 1999, until they finally reappeared in October 2004.

Even with above-average flow, there's concern about the runoff efficiency of the basin. While precipitation has been about 85 percent of average, inflows to Lake Powell have been only about 50 percent of average. This results from soil moisture deficits, which Tom Pagano of the Natural Resources Conservation Service likened to high-interest credit card debts that take significant 'extra revenue' to pay back.

Soil moisture rose dramatically in parts of the Southwest with the extreme storms in October, to levels usually experienced only during spring snowmelt. But the Upper Colorado Basin notably missed out on that precipitation. Also, short-term relief of surface soil moisture should not be confused with long-term recovery to pre-drought groundwater, riverflow, or reservoir conditions. According to Doug LeCompte of the Climate Prediction Center, even the wettest winter on record in the region would raise the Palmer Drought Index (an indicator of soil moisture) only slightly.

The Colorado Basin River Forecast Center has been making early outlooks of Lake Powell inflows using their probabilistic forecast system. Their most recent outlook, computed November 7, gives a 50 percent chance of unregulated inflows above 6.7 million acre-feet (MAF) during April–July 2005, but also a 50 percent chance of having lower inflows. That's higher than the 5.1 MAF outlook estimated in August, but still lower than the long-term average of 7.9 MAF.

There may be some cause for optimism based on the weak El Niño declared earlier this year. El Niño is sometimes correlated with increased winter precipitation for the Southwest. But as Klaus Wolter of the Climate Diagnostics Center stressed, El Niño has many flavors. This event's ocean temperature patterns are quite unlike the 1982/83 and 1997/98 events that brought wet winters and high water supplies to the Southwest.

In fact the hope of El Niño may turn to pessimism when looking at similar El Niño events in the past. One analog includes the dramatically dry winter of 1976/77 and others suggest a drier winter is more likely than a wetter winter unless the El Niño strengthens rapidly over the late winter and spring. Another concern is the strong trend of warmer winter temperatures that can decimate snowpacks and dramatically reduce subsequent river flows, like in March 2004.

A pragmatic perspective is to consider how to avoid the worst consequences if Colorado River flows and reservoir levels continue to be low—Lake Powell is unlikely to be refilled in 2005. But El Niño, watershed conditions, and climate outlooks should be monitored and reconsidered in a couple months before taking any irreversible actions.

Holly Hartmann is an assistant research scientist in Hydrology and Water Resources at the University of Arizona

The future Colorado River: Will it deliver?

Rising temperatures will put stress on both supply and demand

BY MELANIE LENART

Climate change could further humble the mighty Colorado, already bowed by the ongoing drought and shrunken by a growing population of Arizona users.

Currently, the Colorado River meets about two-fifths of Arizona's water needs, with groundwater providing another two-fifths and other rivers supplying most of the remaining demand. But the potential for rising temperatures to decrease the amount of water supplied by the Colorado while simultaneously increasing overall water demand has spread ripples of concern among those who monitor and model the Colorado and other Arizona water sources.

Much of Arizona's Colorado water flows through an open canal system known as the Central Arizona Project (CAP), which delivers river water to Phoenix, Tucson, and other cities, explained Katharine Jacobs during a December press briefing on warming and water supply that was organized by two University of Arizona groups: the Center for Sustainability of semi-Arid Hydrology and Riparian Areas (SAHRA) and the Climate Assessment for the Southwest (CLIMAS).

"In the context of Assured Water Supply determinations, the Arizona Department of Water Resources uses an assumption that the CAP is a reliable supply," said Jacobs, who worked for the ADWR for more than 20 years before joining the UA faculty last year. Under the Assured Water Supply determinations that apply to new subdivisions in central Arizona metropolitan areas, developers must show on paper that there's enough water to support their proposed subdivisions for 100 years.

The current drought already is challenging that assumption, as CAP water users would be the first to have their water supply reduced if a shortage were declared in the Lower Basin states of Arizona, Nevada, and California. The ongoing warming of the atmosphere adds to the uncertainty of the Southwest's water future, Jacobs explained.

"The big issue is whether we can store enough water to offset longer drought periods than we previously anticipated," she said.

Reservoir storage in Lake Powell and Lake Mead totaled about 23 million acre-feet as of Dec. 15, although only about three-fourths of what remains is accessible. In addition, Arizona has "banked" about 2 million acre-feet of Colorado water via groundwater recharge and other programs since 1996, said Timothy Henley, manager of the Arizona Water Banking Authority.

Reconstructions of past droughts based on tree-ring records indicate that two rivers supplying Phoenix with water, the Colorado and the Salt, can be in drought simultaneously, as CLIMAS Project Manager Gregg Garfin noted during the briefing, showing preliminary results of an analysis by Katherine Hirschboeck and David Meko of the University of Arizona Laboratory of Tree-Ring Research. The final results of the study are expected to be released publicly in early 2005 by the Salt River Project.

Governor Janet Napolitano also sees a connection between warming temperatures and regional water supplies and noted her concern in an aside following a Water Listening Session in Tucson last week.

"I'm concerned about climate change in a lot of different ways. I think the drought is certainly an outgrowth of climate change," the governor said, adding that she believed national legislation was needed to address the problem. Nationally, the bipartisan "Climate Stewardship Act," cosponsored by Arizona Senator John McCain, calls for reduced emissions of carbon dioxide and other greenhouse gases that trap heat at the surface.

Greenhouse warming is expected to bump up the average annual temperature in the Southwest by about 3 to 4 degrees Fahrenheit over the next 45 years, according to an analysis by Martin Hoerling, Jon Eisheid, and Gary Bates of the National Oceanic and Atmospheric Administration (NOAA) that involved averaging four different global climate models.

The link between greenhouse gases and temperature is fairly predictable. Long-term temperature fluctuations tend to go up and down with atmospheric carbon dioxide levels in time, and temperature projections for the future mirror the growing accumulation of carbon dioxide and other greenhouse gases in the atmosphere.

The relationship between temperature increases and precipitation is less certain. While some climate models predict an increase in precipitation for the Southwest, others predict a decrease or a lack of change. However, most predict a greater proportion of rain compared to snow as spring arrives earlier in the year and fall lingers later. The decline in snow days could affect overall streamflow, as the Colorado River depends upon spring snowmelt for much of its annual volume (Figure 1).

But even if precipitation rates remained the same—or increased only somewhat—the projected change in temperature alone would impact water supplies, Jacobs noted at the briefing. An increase

continued on page 37

Colorado River, continued

in annual temperature by 4 degrees Fahrenheit, as predicted by the NOAA analysis, could translate into a 5 percent or more increase in evaporation rates, based on calculations by Paul Brown of the UA's Arizona Meteorological Network, she pointed out.

Evaporation from streams and reservoirs consumed about 113 billion gallons (0.35 million acre-feet) in the Lower Basin from Hoover Dam on down during 2002, not counting the CAP system, based on figures in a U.S. Bureau of Reclamation report. A 5 percent increase would boost the amount lost to evaporation by another 5.6 billion gallons annually, enough water to theoretically support 70,000 southwestern residents. (There are about 326,000 gallons in each acre-foot of water, enough to support an average family of four for a year.)

Evaporation occurring before the water reaches the Colorado riverbed may prove even more important as climate warms. Evidence indicates the temperature increases will make the river more sensitive to changes in timing and amount of snow and rain, mainly by affecting the rate of water flowing from overland soils to streams, known as runoff.

Basically, drier soils tend to absorb more of the water inching toward streams, much as a dry sponge captures more moisture than a wet one.

For instance, a hydrological model developed by University of Washington researchers to represent the years 2010 to 2098 found allocations to the Lower Basin states could fall short one-fourth of the time in their climate change scenario. They paired the projected increasing temperatures with fluctuating precipitation rates that averaged about 4 percent lower than the norm for 1950 to 1999. This slight decline in precipitation yielded a 16 percent reduction in runoff.

The University of Washington model did not simulate a potential increase of rain-on-snow events, on the other hand. These events can cause floods that help fill reservoirs, although reservoir gains from these events tend to mean losses in groundwater recharge. At any rate, the sensitivity of the system should concern water managers, the authors note in their *Climatic Change* paper (March, 2004).

"The bottom line implication of the paper is that the system is in a very fragile equilibrium. Very small changes in precipitation are able to reduce the runoff so the system is no longer in equilibrium," explained Professor Dennis Lettenmaier, one of the five researchers who designed and tested the model.

Runoff tends to decline at a faster rate than precipitation decreases, in reality as well as in their model. For instance, the mere 1 percent decrease in precipitation in the Colorado River Basin during 1995 that they cite in their paper translated into a roughly 7 percent drop in basin-wide streamflow that year, based on U.S. Bureau of Reclamation data.

Meanwhile, warming temperatures are likely to increase demand for water by both agricultural and urban users, as Jacobs and SAHRA colleague Gary Woodard noted during the briefing. Agriculture accounts for about 70 percent of Arizona's water use and 80 percent of the state's Colorado River use. Applying the 80 percent ratio to Arizona's annual allocation of 2.8 million acre-feet would make this about 730 billion gallons.

Of this, about 400 billion gallons of water a year evaporate from croplands, judging from USBR data for 2002. The 5 percent increase in evaporation rates that could accompany a 4-degree-Fahrenheit temperature increase, then, could consume roughly 20 billion additional gallons.

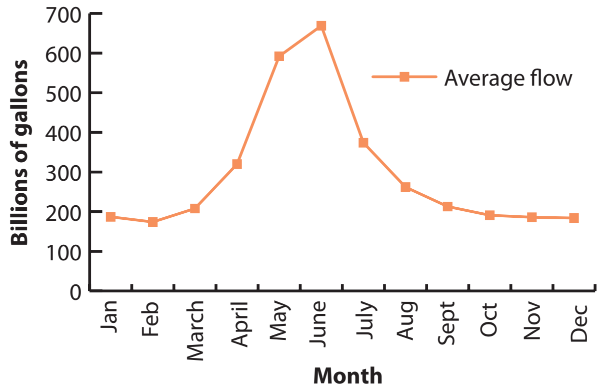


Figure 1. Values for average monthly flow of the Colorado River, above, are based on U.S. Bureau of Reclamation monthly reconstructions for 1922–2003, using actual measurements of streamflow at Lee's Ferry, Arizona, coupled with reports of withdrawals by Upper Basin users. Most of the Colorado's volume comes during spring and summer, as snow melts on the Rocky Mountain peaks that provide the bulk of the river's volume. This makes the river sensitive to changes in snow cover.

At the same time, higher temperatures will stretch out the growing season, as spring comes earlier and fall stays later. This can lead to increased water demand for urban landscaping, Woodard said. Although the higher carbon dioxide levels actually improve the water efficiency of plants, the potential water savings from this factor may well be lost to the longer growing season, he said.

Higher evaporation rates will boost water demand among pool owners as well. Further, higher temperatures will increase the demand for electrical power, which consumes water through cooling towers, Woodard noted. Cooling towers become less efficient with warmer temperatures, he added.

The future Colorado River could be stretched thin for other reasons in addition to rising temperatures, including policy changes and growing population. At this point, Arizona is using all of its annual allocation (Figure 2), although some of it goes for groundwater recharge programs.

continued on page 38

Colorado River, continued

Tribal needs will be a source of demand in years to come. This increase will expand as officials from many sides negotiate and litigate to implement a policy that has technically been on the books for decades: carrying out the promise to share Colorado River water with the American Indians living on Arizona's many reservations.

By some accounts, the annual amount of Colorado water owed to the various tribes surpasses the 2.8 million acre-feet allocated to the entire state. By all accounts, tribal rights to a share of the Colorado can only increase in years to come. Legal wrangling continues while some reservation residents continue to haul water to their homes.

When groundwater is factored in, most of the increasing demand for water in the future seems likely to come from population growth as developers build new subdivisions around the state.

"We anticipate that the Arizona population will continue to grow at the rate it has in the last decade," the governor told those attending the Water Listening Session in Tucson. A repeat of the last decade's 37 percent increase would grow the state population to about 8 million people by 2014, up from 5.8 million in 2004, according to statistics from the Arizona Department of Economic Security.

Although public officials tend to talk about population growth as though it's unavoidable, some area residents aim to slow the pace to a "managed growth."

For instance, 6 of the 17 people who addressed the governor during the listening session cited concerns that nearby developments were threatening local groundwater stores, and most of these comments received a hearty round of applause from the 100-plus people in attendance. Conservation of water and riparian areas was the only theme that received more commentary, with nine people weighing in, not counting those who pointed accusing fingers at golf courses. A few tackled both conservation and population growth.

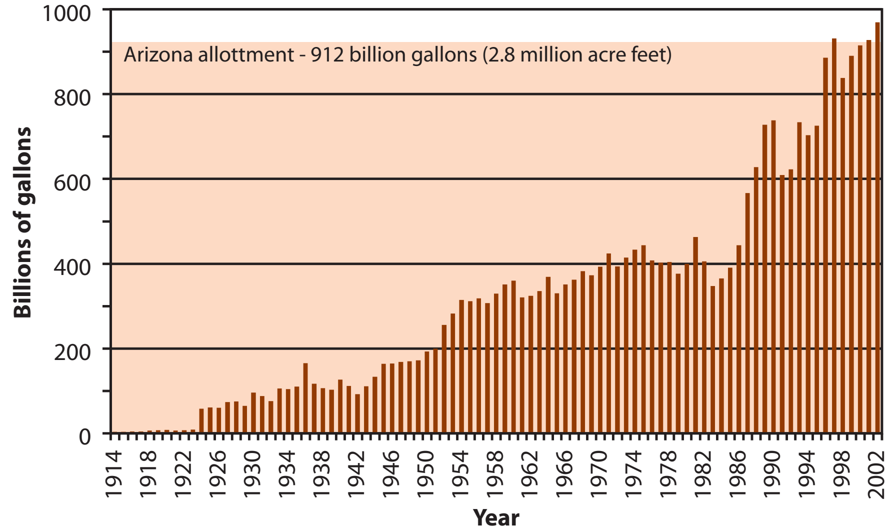


Figure 2. The proportion that Arizona uses of its 2.8-million-acre-feet Colorado River allocation has climbed in recent years. In years of declared surplus, it can even exceed the allocation. Some of the increase in use since 1996, however, relates to "banked" Colorado water as part of an Arizona program to recharge groundwater. Source: U.S. Bureau of Reclamation data.

"Existing people have to reduce their existing use in order to allow other people to come in," said area resident Tricia Gerrodette, who likened living amid the limited resources in the desert to being on a lifeboat. "At some point, if you allow too many people on that lifeboat, everyone will die."

Humans have the advantage of being able to walk, drive, or fly away from a region with dwindling water resources, but many other species are less fortunate. The ongoing climate change could prove fatal for some native riparian species, especially when coupled with the continuing diversion of water out of the river and into cities and croplands.

For human residents of the Southwest, the likely outcome of future shortages is an increase in the cost of water as the regional bidding for a scarce resource becomes more competitive.

As Robert Glennon, a UA law professor and the author of "Water Follies" noted, planners of a resort near the Grand Canyon would have been willing to shell out $20,000 to buy and transport each acre-foot of delivered surface water. (The deal fell through following a Sierra Club lawsuit.) That's quite an increase from the $15 an acre-foot typically paid by an Arizona farmer, he pointed out.

"This development offers a clear vision of what lies ahead. Water is worth a lot more money than people have realized," he wrote in his 2002 book. "Even though water is a scarce commodity, most Americans have not yet faced the conditions that economists call scarcity, which occurs when people alter their consumption patterns in response to price increases."

Southwesterners can expect the era of cheap water to end in the next decade or so, given the guaranteed increase in demand and the likely decrease in supply facing the growing number of users of the Colorado River in Arizona.

Melanie Lenart is a postdoctoral research associate with CLIMAS. For more on the connection between climate change and western drought, see the December 2003 feature article at http://www.ispe.arizona.edu/climas/forecasts/articles/climatechange_Dec2003.pdf.

Global warming could affect groundwater recharge

By Melanie Lenart

Less than a week after record streamflow filled the six-lane-highway sized Rillito River with churning brown water, barely a puddle remained visible in the Tucson stretch near River and Park. A logjam piled up against a bridge bore silent testimony to the late July flood, which seemed to have passed on (Figure 1). Actually, some of it had passed underground. Judging from previous events, remnants of the floodwaters continued to trickle toward the water table about 120 feet below the barely moist surface.

Groundwater reservoirs remain mysteriously out of sight, making fluctuations of these important sources of southwestern water difficult to measure. It's even more challenging to project how they might fare as climate changes with the ongoing global warming.

Recent research shows that groundwater replenishment in the Southwest depends largely on floods, especially winter floods. This, in turn, means the fate of El Niño and snow cover likely hold the key to how groundwater recharge rates will change as the climate warms. The fate of El Niño as climate continues to warm remains unclear. Snow cover changes are more predictable. The changes they will wreak on groundwater recharge is less predictable, but not encouraging.

Figure 1. Tucson resident Robert Segal stands by debris collected by supports of the First Avenue bridge where it crosses the Rillito River. The July 31 high waters that carried the logs had moved downstream or underground by August 5, when this picture was taken.

Short-term recharge

"The thing that really drives groundwater recharge are these large storm events," which typically occur in winter, explained John Hoffmann, brandishing a graph showing episodes of groundwater recharge along the Rillito from one of his studies. The U.S. Geological Survey hydrologist pointed to the boost in aquifer levels during the winter of 1998, when the Rillito flowed for a month straight.

"That sustained flow provided an opportunity for focused recharge," Hoffmann added during a conversation in his Tucson office that also included Stan Leake, a hydrologist who has considered how climate change might impact groundwater recharge processes. Like the 2006 flood, a 1999 summer flood during the study disappeared more quickly, providing less time for recharge (Figure 2).

Riverbeds focus recharge in space as well as time, Leake explained. Unlike most of the southwestern lowlands, riverbeds do not contain a layer of caliche. Composed of calcium carbonate—roughly the same material as concrete—caliche blocks the downward flow of water. Caliche forms when the carbonate in rainfall joins with the calcium in the soil, often combining as the water evaporates back up through the soil horizon.

Along with riverbeds, mountain fronts also serve as major recharge sites. The alluvial fans of sediment spreading across the foothills can soak up the melted snow streaming down from the peaks as well as the monsoonal rainfall of summer that the mountains help spur. Just how much recharge occurs along mountain fronts versus in riverbeds depends on the region and the climate that year, noted James Hogan, the assistant director of SAHRA, a University of Arizona consortium of water researchers. His work in the San Pedro Basin of southeastern Arizona suggests the recharge occurring in riverbeds can range from zero, such as during a dry year like 2002, up to 40 percent during a year with a strong monsoon, such as 1999.

Like the oil and natural gas contributing to global warming, groundwater exists in the porous spaces of rocks and sediments. Also like these fossil fuels, groundwater may have moved into its belowground location thousands of years ago or more. That's why some geologists like to refer to it as "fossil water" and speak of "mining" groundwater. The latter refers to taking out more groundwater from an aquifer than can be recharged on average in the time frame considered.

Although the Southwest contains massive amounts of fossil water, mining

continued on page 40

Groundwater, continued

it can cause the ground to subside—a potential disaster from a homeowner's point of view. In Tucson, subsidence has caused three to four feet drops in some sections around the central area.

So far, the subsidence hasn't caused widespread damage to homes and roads—but it could in the future if water mining continues unabated, explained Tim Thomure, the lead hydrologist for the Tucson Water Department. That's why the department has been promoting the use of renewable water supplies to replace groundwater mining.

'Artificial' recharge

Along with surface water supplied by rivers, renewable sources can include the water that measurably replenishes the aquifer. In Tucson's case, it also includes some of the city's Colorado River allocations now deployed in the Avra Valley artificial recharge project. It's called artificial because the water source is not local precipitation. But the recharge project is helping officials and researchers better understand recharging processes, whatever the water source.

"Your key point is you have to get through the surface—your top 10 to 20 feet," Thomure explained during a recent interview. Once it filters down that far, it should be safe from evaporation, as long as plants can't reach it. Then it has time to move around pockets of clay or other impermeable barriers on its long journey to the water table, which can take a year at the Avra Valley site. The artificial recharge project is highlighting another value of floods. Floods tend to scour channels, clearing out debris and organic matter from the riverbed. In the artificial recharge arena, officials must find ways to mimic the cleansing action of floods or clogged pores can impede their efforts.

Without floods, an impenetrable layer of mud or algae can build up on the channel bottom. Scouring the riverbed with heavy equipment can help, but creates potential erosion problems. Where the recharge source involves wastewater effluent, the high nitrogen levels boost algae growth so much that workers have to allow the sediments to dry out every day or two.

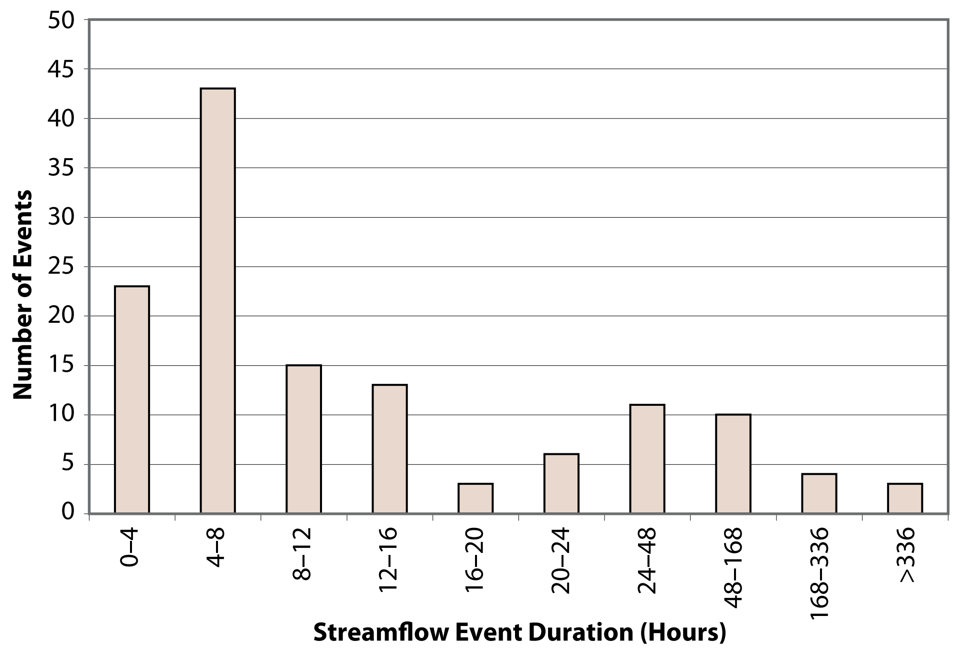


Figure 2. The number of hours during which waters soaked the Rillito River, an ephemeral stream, rarely lasted more than a day (24 hours) between 1990 and 2002 at USGS site 9485700. Graphic adapted from a figure published in the August 5, 2006, issue of *Water Resources Research* (Volume 42, number 8, page W08405-7).

Long-term recharge

To consider the long-term flow of groundwater, researchers favor using isotopes. For the past 15 years, University of Arizona (UA) geologist Christopher Eastoe has been employing isotopes from carbon, oxygen, hydrogen, and sulfur along with tritium to explore the sources and flow patterns of groundwater in the Tucson Basin.

Using equipment at the UA campus, Eastoe can compare chemical patterns in groundwater patterns to those in rainfall. For instance, the ratio of slightly heavier oxygen atoms—known as isotopes in this context—to the more common variety can reveal whether their H_2O source fell during summer or winter.

This chemical detective work has allowed him to identify groundwater signatures that point to their sources—in space as well as time. His paper on the topic, along with others including one on James Hogan's research mentioned above, can be found in the book *Groundwater Recharge in a Desert Environment* (American Geophysical Union, 2004).

Winter storms rule

Eastoe's work over the years, with others, has highlighted the importance of winter precipitation for groundwater recharge.

"We have almost no influence of summer rain in the (Tucson) basin regarding recharge," judging from the isotopic signature in the top 600 feet of the water table, Eastoe said in November. This fits with the observations that winter storms tend to be larger and linger longer on the landscape, while summer storms tend to come in flashier local events and evaporate quickly.

continued on page 41

Groundwater, continued

"To the extent that you keep the water in the river for three months rather than three days, there's far more potential for recharge," noted Katharine Jacobs, executive director of the Arizona Water Institute.

Although Eastoe is still pulling together other research, preliminary results indicate the tendency for winter precipitation to drive groundwater recharge probably holds for many basins throughout the Southwest. He noted that graduate researcher Arun Wahi's work shows the telltale signs of winter-dominated groundwater inputs even in the basin underlying the San Pedro River, where monsoon rain comprises about two-thirds of precipitation in a typical year.

USGS hydrologist Don Pool's research also supports the interpretation that winter storms drive recharge. He found the high-flow events that are good for recharge were more likely to occur during El Niño events at the three stretches he considered: the San Pedro River at Charleston and Tucson's Rillito and Sabino creeks (*Water Resources Research*, November 2005). La Niña conditions almost always meant low winter/spring river flows. However, about a third of the remaining years corresponded to years with high waters on at least one of the rivers.

El Niño years tend to boost winter and spring rainfall in the Southwest, with little direct impact on summer and fall precipitation. During El Niño events, warm water drifts to the eastern side of the Pacific Ocean Basin, often pulling the jet stream south into saguaro territory. During La Niña years, cooler eastern Pacific temperatures help create a ridge that deflects the jet stream and its associated rainfall.

Impacts of changing climate

El Niño events have become more frequent and pronounced since the mid-1970s, although a lengthy La Niña event from 1998–2002 helped provoke the southwestern drought. Global warming accelerated during the same three decades, but climatologists are reluctant to use this as evidence that El Niño events will dominate future climate.

El Niño can fall into decades-long patterns from other causes besides global warming, as evidence from past climates show (*Southwest Climate Outlook*, January 2006). Computer models considering how this crucial pattern might shift with additional warming show a wide array of results (*Advances in Geosciences*, 2006). Scientists disagree on exactly how the ocean fluctuates from El Niño to La Niña and back, much less on how the mechanisms behind the fluctuations will change as oceans warm (*International Journal of Climatology*, April 2006).

The fluctuations, which affect precipitation patterns throughout the world, depend on differences in temperature between the western and eastern Pacific, not merely the temperatures themselves. While it's straightforward to project an upward climb in overall temperatures for both land and sea, it's more challenging to predict how the dynamics will play out.

The fate of snow cover, on the other hand, is easier to project because it relates directly to the warming. As temperatures rise, snowline creeps up the mountaintops. Snow cover shrinks in time, too, as warm temperatures extend their reach forward into autumn and backwards into spring.

Already researchers have been documenting a trend for more precipitation falling as rain rather than snow over the past half century throughout much of the West (*Journal of Climate*, September 2006). These changes are bringing a documented shift forward in time for the peak river flow that comes with spring thaw (*Journal of Climate*, April 2005). This has some researchers worried about the fate of groundwater recharge.

"As we change toward more rain away from snow, that has the potential to decrease the amount of recharge," Leake said. In higher mountain ranges of the Southwest, the melting of snow creates steady springtime river flows that recharge aquifers in the valleys below, he added.

USGS researcher Michael Dettinger expressed similar thoughts. "As the snowline retreats to cover smaller and smaller areas, and as the snowpack itself declines because of more rain and less snow and more intermittent melting… it seems really likely that recharge will decline in many parts of the Southwest," he said during a telephone conversation.

Warming temperatures also can turn some winter storms into the flashier events usually associated with the Southwest summer. He recalled a May 2005 storm around California's Yosemite Valley. Warm temperatures allowed the rain to cover a much larger area than typical for that time of year, with snowfall limited to elevations above about 10,000 feet. As a result of the extensive area involved, a mere one inch of rainfall resulted in a flashy valley-wide flood.

Floods like this can provide some recharge, much as the here-and-gone Rillito flood this summer did. But it's unlikely to provide the same groundwater boost as it would have if the same amount of precipitation had fallen as snow and then melted over time, feeding rivers for months on end. If winter storms start acting like summer storms, groundwater aquifers could pay the price.

Melanie Lenart is a postdoctoral research associate with the Climate Assessment for the Southwest (CLIMAS). The SWCO feature article archive can be accessed at the following link: http://www.ispe.arizona.edu/climas/forecasts/swarticles.html

Water, energy, and climate linked in complex ways

Arizona water summit brings water and electrical connections to light

BY MELANIE LENART

Rain and snow yield water, flowing on the surface or replenishing groundwater aquifers. Water supports energy production—it's tapped for hydroelectric power or cycled to cool electrical plants. Most electrical plants, in turn, emit greenhouse gases, which warm the planet and disrupt water cycles.

These and other interconnections between water, energy, and climate fueled discussions at an Arizona Water Summit in Flagstaff earlier this month that attracted educators, tribal members, commercial interests, and policy makers, including the governor of Arizona.

Governor Janet Napolitano last year requested that the state's three universities address the links between water and electricity, summit organizer Gary Deason of Northern Arizona University (NAU) reminded as he introduced a session on the topic. Along with summit planning, researchers from NAU, the University of Arizona (UA) and Arizona State University (ASU) have been working together to launch a "virtual water university," also at the governor's behest. (See story to the right).

Concern about climate variability and global warming translates into worries about water and energy. The recent drought drained many reservoirs serving Arizona to half empty by mid-2004, including Lake Mead and Lake Powell, which store Colorado River water. Dams associated with these and other reservoirs together provide about 8 percent of Arizona's electrical power (Figure 1).

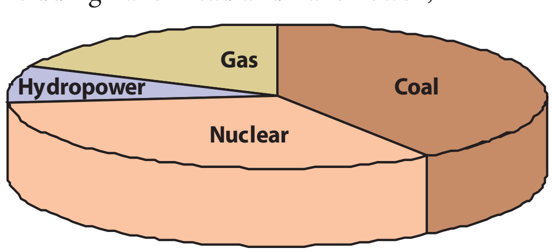


Figure 1. The share of electrical power generated by fuel types is shown above, based on 2002 data from the Energy Information Administration.

Although the smaller Arizona reservoirs are refilling at an encouraging rate, especially those serving Phoenix, it could take years to decades to refill the major reservoirs that store Colorado River water, noted Gregg Garfin, program manager for the UA Climate Assessment for the Southwest (CLIMAS).

Governor Napolitano said she suspects the drought will "reassert itself" despite the relatively wet water year that began last October, a position that many climatologists also hold. During a summit talk, Garfin illustrated the potential for more drought ahead by pointing out droughts of 10 to 20 years in long-term precipitation records for the Southwest derived from tree rings.

Tree rings and other climate proxies also have been used to reconstruct northern hemisphere temperature patterns for the past millennium. John Brock of ASU showed summit participants the famous "hockey stick" reconstruction of global temperatures (Figure 2). The record shows an ongoing trend toward increasing temperatures, which scientists agree relates mainly to the input of additional greenhouse gases from fossil fuel and forest burning.

Water vapor is the most prevalent of the atmospheric greenhouse gases that warm the planet to about 60 degrees Fahrenheit overall. Without the greenhouse effect provided by water vapor and other atmospheric gases, the Earth's average temperature would be a freezing 15 degrees Fahrenheit, analyses indicate.

continued on page 43

Virtual water university

BY MELANIE LENART

A "pet project" of Arizona Governor Janet Napolitano's—a virtual water university that pulls together on-line expertise from Arizona's three universities—took a step forward this month with a newly launched interactive website.

Gary Woodard of The University of Arizona (UA) unveiled a website called "Arizona Water," the first product of the virtual university's collaborative efforts. The website offers a searchable database on experts, projects, facilities, and publications by about 420 water researchers working at the UA, Northern Arizona University (NAU) and Arizona State University (ASU). It is posted at www.arizonawater.org.

The virtual university "breaks down walls" between the universities, providing a science-based pool of resources to assist state decision-makers at a variety of levels, Governor Napolitano told summit participants during the August 4 dinner. One of the tasks of the university will be to improve predictions of future climate conditions in order to reduce vulnerability of water supplies.

"My view is that we can't do good planning without good data. That has to be the foundation for the public policy choices that need to be made," Napolitano said.

During a breakfast meeting about the virtual university the next morning, the UA's Kathy Jacobs stressed that

continued on page 44

Complex links, continued

Given the additional input of greenhouse gases from human activities, scientists project the planet will warm by another 3 to 10 degrees Fahrenheit by the end of the century. The variable influence of water vapor helps confound precise projections (as does the possibility that society may change its patterns of energy use). Water vapor tends to moderate climate, working to dampen daytime temperatures through evaporative cooling while warming nighttime temperatures by trapping heat near the Earth's surface.

In the West, the warming is ramping up even faster than projected, although the heat island effect from growing cities also contributes to rising temperatures. Both greenhouse warming and urbanization have the greatest effect on nighttime temperatures.

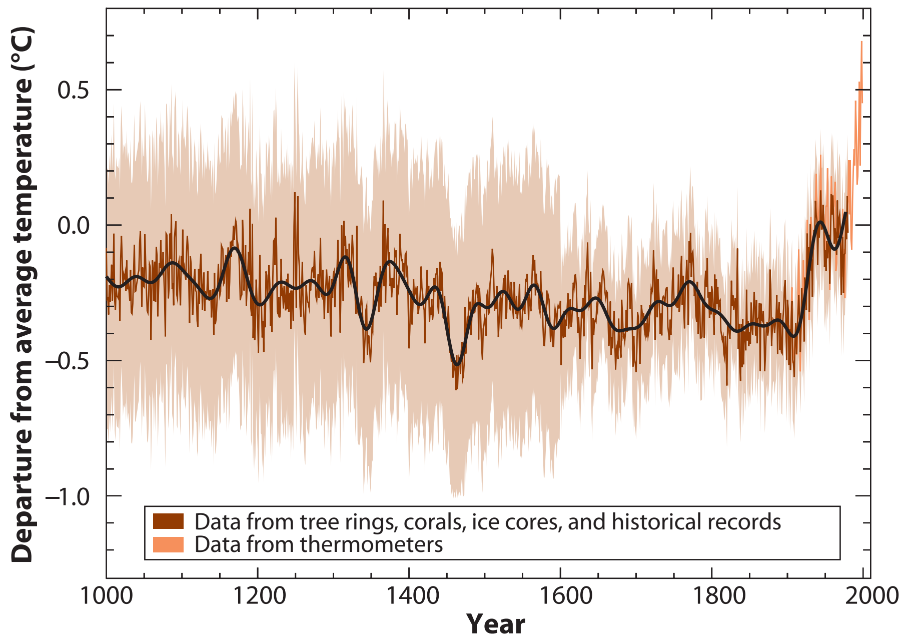


Figure 2. The instrumental record of northern hemisphere temperature (pink) is superimposed on a 1,000-year temperature record for northern hemisphere reconstructed from annual tree rings, coral growth, and ice core layers (brown, with range of potential error shown in tan and "smoothed" average shown in black). Its shape, with an abrupt rise in modern times, has led some to dub the record a "hockey stick." Source: Intergovernmental Panel on Climate Change Third Annual Assessment, 2001.

The ongoing warming threatens to wreak havoc on the delicate balance of southwestern water supplies, in part because of a trend toward earlier snowmelt that could strain Colorado River allocations. (see *Southwest Climate Outlook [SWCO]*, December 2004). To top it off, some fear that drought could become even more commonplace as evaporation rates climb with temperatures and precipitation becomes more variable. Many people advocate taking steps to reduce this risk (see *SWCO*, December 2003).

"We can mitigate climate change by decreasing our dependence on fossil fuels," Garfin suggested at the summit. This "no-regrets" strategy would address public health issues related to air quality. Society can also adapt to climate change, he added, by improving water conservation, water banking and irrigation practices.

A recent survey of Arizona irrigators suggests that nearly half a million acre-feet—roughly 160 billion gallons—of Colorado River allocations are likely to be freed up in the near future by farm sales, noted the UA's George Frisvold. However, expanding development in Arizona will continue to drink up any savings from the decline in agricultural use for irrigation, he warned.

"The plain fact of the matter is that with population growth in Arizona, Nevada and California, the Colorado River is being strained to the utmost," Governor Napolitano said at a summit dinner.

In addition, pending legal decisions are expected to require that Arizona's allocation of the Colorado be more fairly shared with the Native Americans living on tribal lands. "There are [water] rights that are going to be given to the Navajo and Hopi, appropriately, and people are going to have to live with that," as Arizona Legislature Representative Tom O'Halleran reminded the group.

Many Diné people living on the Navajo Reservation stretch a 55-gallon-drum's worth of water through an entire week, Justin Willie of the Navajo Waters Information Network told the group. The Hopi adopt a similar approach.

"Many of our people have to drive over 100 miles to haul water for their consumption, for their livestock, for their farms," said Wahleah Johns, a Hopi with the Black Mesa Water Coalition. "It's appalling."

Johns, Willie, and dozens of other Native Americans reminded summit participants that "water is life," and urged people to see water as sacred—not as something that can be bought and sold like any other commodity.

"One of the big themes was that we have a spiritual connection to water," Enei Begaye of the Indigenous Environmental Network said, reporting on a tribal water caucus held in Flagstaff the previous day. About 50 people from tribes throughout Arizona and New Mexico attended the caucus, and many stayed for the summit.

But prayer must be balanced with activism, Begaye counseled. "The issue of who controls the water is a huge issue," she said during a discussion session she

continued on page 44

Complex links, continued

moderated on the commodification of water. In Arizona and many parts of the country, groundwater pumping remains mostly unregulated, and it remains legal for companies to profit privately from water extracted from a shared aquifer.

Tribal members at the summit also expressed concern about the use of pristine groundwater below Navajo and Hopi lands to transport coal slurry from mining operations in northern Arizona's Black Mesa to an electrical plant in Nevada.

Mining operations account for about 2.6 percent of groundwater withdrawals for the state, but about 64 percent of groundwater withdrawals from the aquifer below Hopi and Navajo lands, based on U.S. Geological Survey documents for 2000 and 2003 respectively (available at http://water.usgs.gov/pubs/circ/2004/circ1268/index.html and http://water.usgs.gov/pubs/of/2005/1080/).

The cooling of coal, gas, and nuclear energy plants, accounts for about 2.2 percent of the state's groundwater withdrawals, or 10.9 percent of non-irrigation withdrawals. Counting surface water, it requires about 100 million gallons of water a day. Meanwhile, electricity consumption is growing at about 4 percent a year, Arizona Corporation Commission member Kristin Mayes told the group.

"It used to be that every megawatt powered 1,000 homes. Now it's powering 250 homes," Mayes explained. The average Arizona house is larger and less efficient, she said. Also, rising temperatures in recent decades, especially in paved cities like Phoenix, have boosted peak summer electrical demand for cooling.

The increased use of renewable energy was touted as a means of water conservation by Mayes and others during the summit and the sustainability exposition that followed on its heels. While nuclear energy uses the most water to produce electricity, wind and solar energy require virtually no water, except for the occasional cleaning of windmills and solar cells, speakers indicated.

Northern Arizona is well-suited for both wind and solar energy, Lane Garrett of ETA Engineering in Tempe explained during a workshop. The systems work well in tandem, in part because winds tend to blow the hardest on cloudy days and during the monsoon, Garrett indicated. (For a summary of Arizona's renewable energy potential and background on the Hopi solar enterprise NativeSUN, see: http://www.energyatlas.org/PDFs/LowRes/atlas_state_AZ.pdf).

Renewable energy fits well with tribal culture, and suits remote locations far from the grid, summit participants noted. The renewable model also interests Arizona residents concerned about sustainability. Napolitano appears to be among the latter: She chose "Creating Sustainability in the West" as this year's theme of the Western Governors Association, which she chairs.

Garrett's futuristic vision of sustainability features people using the wind and the sun—two elements as revered as rain by many cultures—to produce energy, along with hydrogen to store the energy generated by windmills and solar cells. Renewable energy sources have a neutral influence on global climate, he reminded, and lead to saving water instead of evaporating it in fossil fuel and nuclear power plants. In a desert region, where the sun is omnipresent and water is scarce, he has hope that this vision will continue to move beyond a mirage.

Melanie Lenart is a postdoctoral research associate with the Climate Assessment for the Southwest (CLIMAS). The SWCO feature article archive can be accessed at the following link: http://www.ispe.arizona.edu/climas/forecasts/swarticles.html.

University, continued

the virtual university's success will depend on it having a "cyber backbone" to make data available and accessible to a variety of users. She urged researchers in attendance to begin preparing datasets, along with the information required for their appropriate interpretation, for web distribution.

Plans for the web-based decision-support system include a variety of accessible databases, interactive maps, information on trend analyses, and easy-to-use models involving forecasts and scenarios.

During a question and answer session, the governor said she agreed with a summit participant's comment that the university should tap into tribal experts as well as university experts on water issues, particularly water conservation.

Input from the tribes will be solicited through the universities for at least the initial stages, the governor's chief of staff for operations, Alan Stephens, specified during the follow-up breakfast session. For instance, NAU's Institute for Tribal Environmental Professionals will be among the core groups involved, NAU's Rand Decker noted.

Though the Arizona Legislature has not provided any funding for the virtual university, the Board of Regents has pledged $150,000 to cover salary and expenses for an executive director of the virtual university. State officials indicated they envision the university becoming self-sustaining through federal and private foundation grants as well as contributions from industry.

The website, which was created by the University of Arizona's Water Sustainability Program, is housed at SAHRA, the NSF Center for Sustainability of Semi-Arid Hydrology and Riparian Areas.

Landscape Response

Landscape Response Foreword
By Thomas W. Swetnam

In the time frame spanning the writing of the chapters in this section, the scientific community has gone from considering how climate change impacts might play out on the landscape to documenting how it has begun. Back in February 2004, we wondered whether some of the drastic changes we were seeing in southwestern forests were harbingers of global warming, or only a response to past land use practices, such as a century of livestock grazing, logging, and fire suppression. Research published in the scientific journals since then has confirmed many of our concerns that climate change has played an important role.

High temperatures were identified as one of the likely causes of the 2002-2003 massive die-off event of southwestern piñon and ponderosa pine trees. Drought and bark beetle outbreaks certainly contributed as well. But the recent dieoff was apparently more extensive (about 3.5 million acres in Arizona and New Mexico) than the one which occurred during the 1950s drought, which was at least as dry as the current drought. Higher temperatures during the recent drought seems to have been a critical factor.

A much larger bark beetle outbreak – more than 20 million acres!! – in British Columbia lodgepole pine forests has been strongly linked to warming temperatures, adding further evidence that climate change impacts on ecosystems is beginning in western North America. On another front, recently my colleagues and I found that increasing spring and summer temperatures were correlated with increasing numbers of large forest fires in the past few decades, with the evidence indicating that earlier snowmelt acts to dry out forest fuels, triggering synchronous, large forest fires throughout the West.

Even as we better understand how global warming is changing the landscape, however, we are also recognizing additional complexities in the landscape response. A variety of other factors interact with warming temperature, including annual variability in the climate system and past land management practices.

The previous section described some of the ways global warming interacts with other climate patterns, such as the long-term Pacific Decadal Oscillation and Atlantic Multidecadal Oscillation and the shorter-term El Niño Southern Oscillation (commonly called El Niño). Beyond these climatic factors, there's a human component. The coming section describes some of the ways management practices, climate patterns and global warming affect the landscape in which we live.

To illustrate this complexity of how these various factors can interact, let's consider wildfire patterns in the Southwest. People have been fighting fires in western forests for more than a century, and permitting cattle and sheep to graze in forests for even

continue on page 47

continued

longer. These management practices have changed the dynamics of fire on the landscape in some forests, as our research at the University of Arizona Laboratory of Tree-Ring Research has shown. Before Euro-American settlement, southwestern ponderosa pine forests supported frequent fires, generally of low severity. These surface fires burned along the forest floor with flame lengths of one to several feet in height, maintaining pine forests as open parks with little fuel accumulation in the understory.

Extensive livestock grazing and large-scale firefighting helped create conditions promoting modern-day fires that are often very severe. For example, in the Bullock and Aspen fires that raged on Tucson's Mount Lemmon in 2002 and 2003, respectively, high severity burns completely killed even the canopy trees on roughly a third of the total burned area. Based on our knowledge of fire history reconstructed from fire-scarred trees and the ages of trees in these mountains, that proportion of high severity burn is probably anomalous over at least the past 300 years.

Along with forest management practices, climate variability influences wildfire regimes. Years of above-average rainfall, which occurs more often during El Niño events than during other years, encourage the growth of grasses. These fine fuels prime the landscape for more extensive burns during a subsequent dry year, which is more likely to occur during a La Niña event. We see the influence on forest fires of the fluctuations between these two related climate patterns at many scales, from the Southwest to western North America, and even extending to southern South America.

Yet another contributing factor in these dynamics is the recent spread of invasive grasses in many parts of the West. In the Southwest, introduced red brome and African buffle grasses are increasing exponentially in the Sonoran Desert. These highly flammable grasses resprout prolifically following wildfires, which also kill many native desert plants, such as the iconic saguaro cactus. The exotic grasses appear now to be carrying fire into the woodlands and forests up slope, creating new corridors for fire spread through sensitive habitats and at-risk human communities.

As I mentioned earlier, warming temperatures are apparently now melting the snow packs earlier and desiccating forests more quickly than in earlier decades (before about 1980). This warming has probably contributed to the enormous fires we have seen in the Southwest in the recent decades, but forest changes due to land uses and exotic species, as described above, are likely also involved. However, this pattern of warming temperatures and increasing numbers of large forest fires also shows up in many Northern Rocky Mountain forests, where fire-fighting and other management practices have had relatively little effect on forest structures.

As you can see in this example and the chapters that follow, climate change is rarely the only impetus behind the changes we're witnessing on the landscape. Yet it can make a critical contribution to the result, much like the straw that breaks the

continued on page 48

continued

camel's back. That's why I have found myself compelled, like so many of my fellow scientists, to issue warnings about current and predicted climate change. We're moving into dangerous and generally uncharted territory as we continue to emit greenhouse gases that unequivocally will further warm the planet, resulting in severe ecosystem disruptions.

Some skeptics compare those of us who raise this alarm to Chicken Little, warning that the sky is falling. In reality, I suspect we're playing the role of Cassandra, the tragic prophetess of Greek mythology, portrayed by Shakespeare in his play *Troilus and Cressida*. Unlike Chicken Little's, the prophecies foreseen by Cassandra came true. In the Greek myth, Cassandra's curse was that no one believed her so she was unable to prevent the gloom and doom she foresaw. Still, we must temper our Cassandra-like warnings with the humility that comes from acknowledging the significant uncertainties that persist.

In modern times, people are now recognizing the truth that there are real dangers ahead if we don't take action to curb our greenhouse gas emissions. Therein lies the hope that we can prevent some of the worst consequences of climate change.

This is also the time to think strategically and boldly about our stewardship responsibilities for the landscape and the people and wildlife that live on it.

It is still possible to mitigate coming impacts in some areas. In forests, we need to undertake judicious forest treatments, which will include landscape-scale forest thinning and prescribed burning in order to reduce the risk of severe, large-scale wildfires. In other ecosystems, we need to make similar efforts to increase native ecosystems' ability to adapt to global warming and the changes that come with it.

We have much work ahead, but it is essential work if we want to make the landscape we live in more resilient to climate change. My hope is that the information here and elsewhere will help people understand why it's important to undertake these important steps to reduce some of the risk to our landscape that is posed by rising temperatures. Recognizing the danger ahead can be a blessing if we have the foresight to take action to mitigate it.

Thomas W. Swetnam is professor of dendrochronology and watershed management and Director of the University of Arizona's Laboratory of Tree-Ring Research.

Beetles devastate forests in response to drought

BY MELANIE LENART

If termites were devouring homes at the rate that beetles are killing southwestern trees, cities the size of Phoenix and Albuquerque would be crumbling under the attack.

More than 20 million Ponderosa pines died in Arizona and New Mexico following bug attacks between fall of 2002 and summer of 2003, noted Bobbe Fitzgibbon, an entomologist with the U.S. Forest Service's Forest Health Protection office in Flagstaff. Another 50 million piñon trees died in 2003, she added during a presentation to tribal land foresters.

Fitzgibbon makes her assessments based on extensive aerial surveys, where dry red needles serve as a telltale sign of mortality within the past year at the one-acre scale. A variety of bugs, mostly bark beetle species, are converting large tracts of southwestern forests from evergreen into ominous red.

The epidemic started in 2002 and worsened in 2003 throughout the West, with virtually every state west of the Rockies except Nevada suffering from the onslaught. And there's no sign that the pest outbreak will subside anytime soon—especially if the entrenched drought marches on and temperatures continue to climb.

The drought connection

Drought has a close association to an increase in bark beetle attacks, for a known physical reason. Trees typically defend themselves against beetles by "pitching them out" with their sap. Drier conditions mean less sap flow, however, so beetles find it easier to penetrate beneath the outer layer of bark during times of drought.

Bark beetle species include numerous species of ips, Douglas-fir beetle, spruce beetle, true fir beetles, round-headed pine beetle, mountain pine beetle, and western pine beetle. Together these beetles damaged about 87,000 acres in 2001, 627,000 acres in 2002, and 1.9 million acres in 2003 in Arizona (Figure A). Overall, the wave of peak insect kill appears to be moving north in time, according to Arizona data provided by Fitzgibbon.

"The ips beetles have been the most important in precipitating this latest outbreak," Fitzgibbon said. Ips beetles traditionally target smaller trees, but in this latest outbreak they are often striking at the tops of relatively large trees, where the bole tapers down.

Ips in Ponderosa forests accounted for 75 and 80 percent, respectively, of the acres damaged in 2001 and 2002. But the ratio dropped to about 37 percent in 2003, when piñon ips took over and attacked 1.1 million acres of Arizona piñon-juniper forest.

Another quarter of a million acres of spruce and aspen trees were defoliated in 2003 in the state by other bugs, such as the western spruce budworm and the spruce aphid. The damage continues to spiral upward in time (Figure A). In addition, drought alone appears to have killed trees on more than 65,000 acres in 2002 and 2003, the data show.

These figures showing millions of acres damaged compare to a previous high for Arizona of 490,000 acres damaged by bark beetles in 1957, Fitzgibbon said. The outbreak followed a devastatingly dry period for Arizona—to this day, 1955–56 retains the statewide record for driest water year.

Climate change impacts

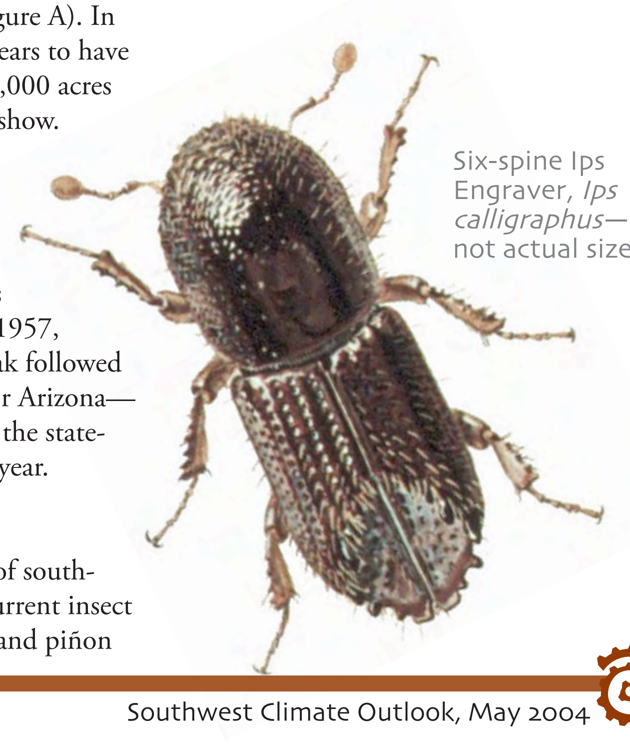
In the Pinaleño Mountains of southern Arizona, similarly, the current insect outbreak among Ponderosa and piñon pines is "an order of magnitude larger and more severe" than the outbreak that occurred during the 1950s drought, noted entomologist Ann Lynch of the U.S. Forest Service's Research office in Flagstaff.

A half dozen different insect species are converging on Mount Graham and other peaks in the Pinaleños. Other southwestern high-elevation forests are succumbing to outbreaks of insect species that were previously innocuous or unknown to the region, such as the spruce aphid, formerly considered a maritime pest.

Why is more forest area being affected in this drought than during the 1950s drought? Lynch suspects the climbing temperatures of the past few decades help explain the difference.

"It's too hot, it's too dry, and there are too many bugs," as Lynch summed it up succinctly to the couple of hundred people attending her plenary session at a Sky Island biodiversity conference in Tucson in mid-May. "The drought is not sufficient to explain the extent of the devastation."

continued on page 50



Six-spine Ips Engraver, *Ips calligraphus*—not actual size.

Beetles, continued

As one example of climate change in action, Lynch focused on the McNary station at 7,000 feet in elevation in northern Arizona's White Mountains. Since 1940, the number of frost days has declined, with the year's frost-free period increasing from an average of 102 days to 147 days. Meanwhile, both minimum and midpoint temperatures for the year increased during this period.

"Much of the Rim country in Arizona was presumed to be beetle-proof," Lynch said. Not anymore. Bark beetles attacked more than half a million acres of Mogollon Rim forest managed by the White Mountain Apache and by Sitgreaves National Forest staff in 2002 and 2003, up from a total of 14,000 acres infested in 2001.

Temperatures from the 1990s on have established new highs for the 100-year plus instrumental record of temperature in the northern hemisphere, with 2002, 2003, and 1998 down as the three hottest years on record. The extra warmth increases the length of the growing—and beetle-breeding—season, while the drop in frost days decreases opportunities to kill off over-wintering broods.

A tendency toward earlier springs and longer growing seasons are among the predicted results of climate changes that are already occurring in the Southwest. Many tree species will face a change in their suitable range as a result of these and other impacts of climate change, including precipitation changes. The higher evaporation rates that accompany higher temperatures also are likely to increase drought frequency.

Ponderosa pine populations could decline in Arizona yet increase in New Mexico, suggested a 1997 study led by Robert S. Thompson of the U.S. Geological Survey. The study also predicted spruce, piñon pine, lodgepole- and Douglas-fir, and gambel oak would decline in the Southwest.

Beetles, and the insects attacking higher elevation spruce and fir forests, may be among the agents of change for this predicted conversion, along with fire.

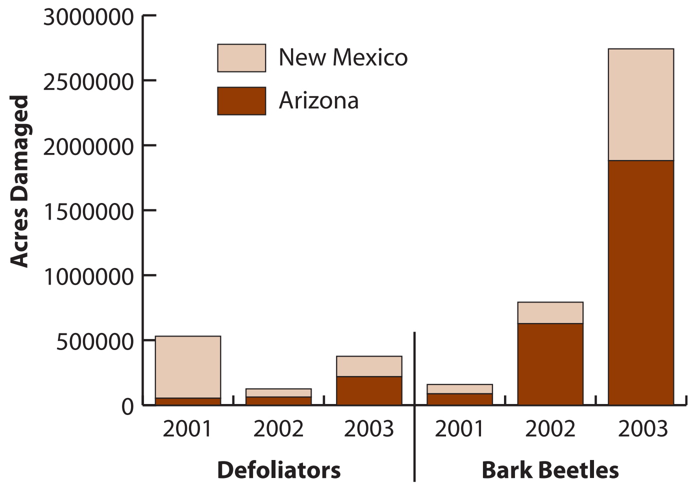


Figure A. Bark beetle attacks have been increasing in the Southwest, especially in Arizona. Bark beetles kill trees by attacking the cambium under the bark, girdling them so that they can no longer transport water to their needles. Defoliators eat the leaves and needles of trees—their attacks are not always fatal.

Management issues

Along with climbing temperatures and drought, Lynch blamed the "overgrown" state of southwestern forests for the ongoing insect attacks. She and other entomologists agreed that reducing the density of the trees in a stand, known as thinning, can help prevent outbreaks.

"I am a big proponent of thinning, thinning, and thinning. I don't care how you do it," Lynch proclaimed, indicating she supported the use of prescribed fires and cutting of some trees to reduce stand densities.

"You have to thin, and then it has to rain or snow," she added. If climate remains dry in the weeks or months following a thinning effort, the remaining trees in a thinned stand may be more vulnerable because of their increased exposure.

Victoria Wesley, a supervisory forester and entomologist for the San Carlos Apache Reservation, agreed that thinning out some of the trees potentially could save the rest. The 400,000 beetle-killed trees within the reservation's 111,000 acres of Ponderosa pine forest were mostly in "inoperable areas," where steep or rocky slopes prevent much management, she told University of Arizona CLIMAS researchers earlier this year.

"I think since we're not thinning those areas, the bark beetles are doing our jobs and going in and thinning," she said.

During an April outing at the reservation, she pointed to a section of green in an area that was otherwise reddened or left barren by bug kill: "That's an area where we thinned."

Jim Youtz, a supervisory forester and silviculturist working for the Bureau of Indian Affairs Fort Apache Agency in the White Mountains of northern Arizona, reported a similar observation.

"All of those big pockets of bark beetle outbreak were in unmanaged stands," he noted after observing a mortality map for the White Mountains shown in a presentation by Fitzgibbon. "Any area that had thinning in the last 10 years didn't have any significant mortality."

"In a way, we're losing trees where we need to lose them," Fitzgibbon agreed, alluding to attacks on dense stands of trees that have turned many Ponderosa forests into fire hazards and sites where drought and bugs are killing off trees that expanded into marginal areas during the wet period of the 1970s and 1980s.

continued on page 51

Beetles, continued

But Lynch worried that the beetles' approach to "thinning" tends to take out the large trees, such as old-growth Ponderosa, whereas forest managers and surface fires tend to thin out the smaller trees in a stand.

Even thinning by foresters can backfire if slash from the cut trees remains in the forest as a potential lure for beetles. For instance, the abandoned slash from thinning operations attracted the round-headed pine beetle to Tucson's Mount Lemmon in the fall of 2001, before the catastrophic wildfires of 2002 and 2003 struck, Fitzgibbon noted.

Similarly, using prescribed burns to thin stands can be risky in the unusually dense forests of this century, as New Mexico forest managers learned the hard way. A prescribed burn morphed into a wildfire and consumed about 47,000 acres of forest around Los Alamos in the summer of 2000.

Meanwhile, the wildfire risk is growing with the number of insect-infested trees on the landscape. The large patches of "red trees," along with the newly attacked trees trying to fend off bark beetle attacks with volatile compounds, feed the fires that can rage through the Southwest during dry months like May and June. Also, some of the dead trees that remain standing on the landscape could stoke fires decades from now, when they finally fall over to act as fuel on the forest floor.

As with catastrophic wildfires, there is little humans can do once beetles decide to consume a tree. Homeowners can water urban trees to prevent attacks, and even use pesticides to protect favorite trees, but these techniques remain too expensive to apply to large tracts of forests, Fitzgibbon said. Even thinning operations carry a price tag of many hundreds of dollars an acre.

That points to one big way forest wood differs from the wood found in and around homes. If bark beetles were devouring homes in Phoenix or Albuquerque, residents would be finding ways to resist the destruction. But the trees in the forest have to rely on their own chemicals to fight for their lives—and they're continuing to lose the battle on a large scale. There's no expectation for an end to the mortality anytime soon.

Melanie Lenart is a postdoctoral research associate with CLIMAS.

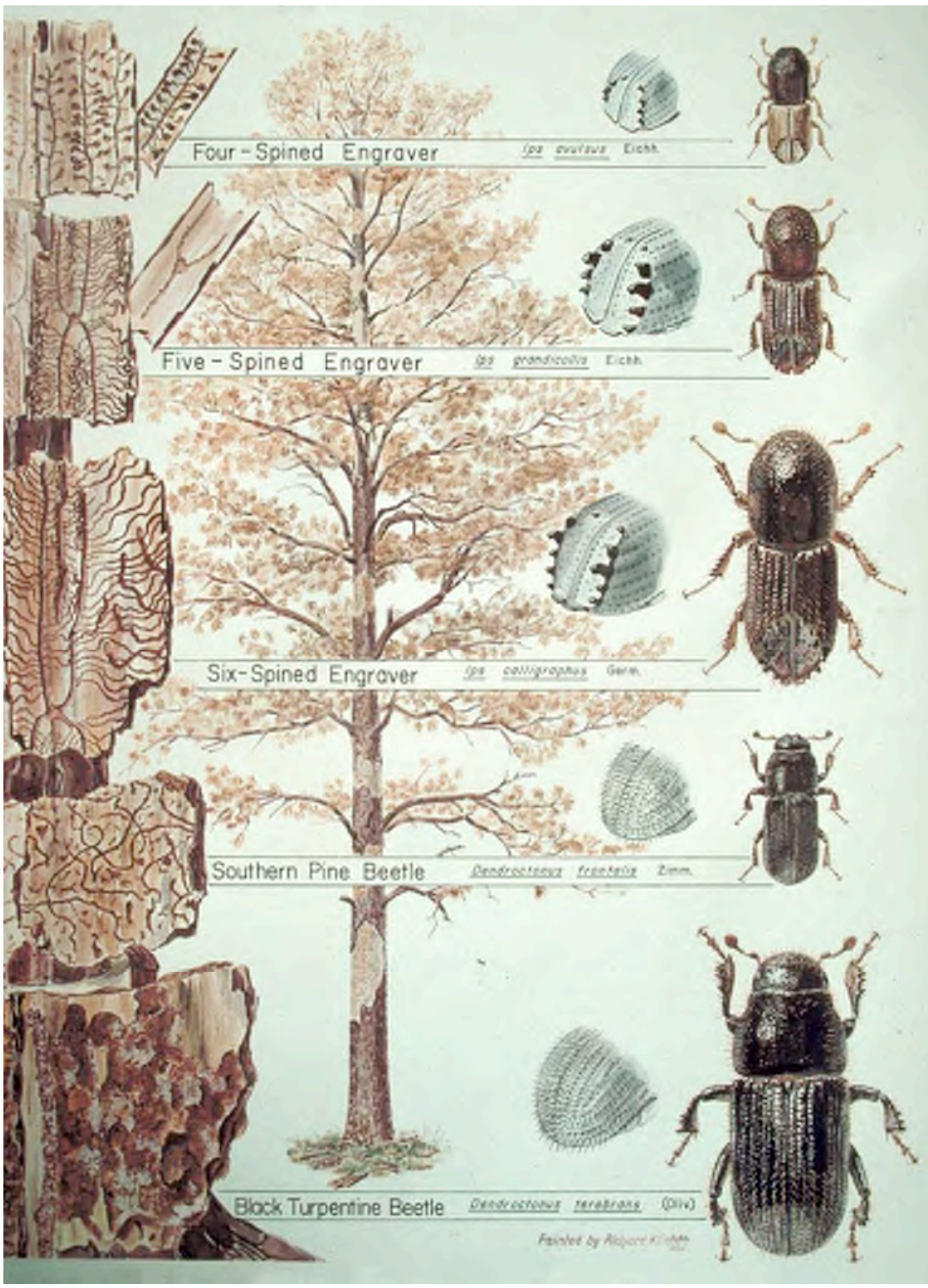


Figure B. Diagram of adults, gallery patterns, and attack sites of 5 bark beetle species (*Ips avulsus, Ips grandicollis, Ips calligraphus, Dendroctonus frontalis,* and *Dendroctonus terebrans*) The Ips beetles, typically about the size of a grain of rice, are the ones causing the most trouble in the Southwest in the recent onslaught on Ponderosa and piñon pines. Damage by *Dendoctonus* species, illustrated here by southern pine beetles and black turpentine beetles, are occurring at a much smaller scale. The images at left show the typical reproductive "galleries" created by the different beetle species under the bark. Image provided by Ronald F. Billings, Texas Forest Service, http://www.forestryimages.org.

Is global warming creeping into Southwest forests?

Evidence building that warming is already affecting the region

BY MELANIE LENART

How do we recognize global warming when we come face to face with it? And if we see it—perhaps in the form of millions of acres of beetle-ravaged forests, or when half the remaining red squirrel habitat goes up in flames—how do we convey that message to the public?

These questions peppered the talks at a Sedona workshop in mid-February that drew forest managers and scientists together for an exchange of views on climate variability and change. The workshop was sponsored by the University of Arizona Cooperative Extension Service, and organizers also included the UA's Climate Assessment for the Southwest and Northern Arizona University.

Climate change, a.k.a. global warming, may be stoking the flames of southwestern wildfires, and promoting "woody encroachment" of grasslands, issues that concern land managers.

Has the warming already started?
Mean annual temperature in the Southwest could rise by as much as a toasty 10 to 14 degrees Fahrenheit or more by the end of the century, pointed out Jonathan Overpeck, director of the UA's Institute for the Study of Planet Earth, citing results of a January 27 *Nature* article.

The Intergovernmental Panel on Climate Change (IPCC) has long predicted global warming would result from the input of greenhouse gases from cars and electrical production. A growing body of evidence suggests the warming already kicked in during the previous century, especially the last quarter (Figure 1).

Mean annual temperature climbed by about one degree Fahrenheit per decade in Arizona between 1970 and 2004, according to an online analysis at the National Climate Data Center website. So a warming of 10 degrees by the end of this century would be merely following the existing trend since 1970. In New Mexico, the ascent was less steep, at about 0.6 degrees per decade for the same time frame. Both rates are higher than the 0.5 degrees per decade for the United States overall for that time period.

In past reports, the IPCC predicted the warming would be greater during cool seasons. In both Arizona and New Mexico, the warming since 1970 is greatest in spring. This mirrors the national trend toward an earlier spring, which in effect means a shorter winter.

The IPCC also predicted that the poles would warm more rapidly than the planet as a whole. In fact, the warming around the North Pole is happening even faster than scientists expected, and many consider the melting ice a harbinger of things to come.

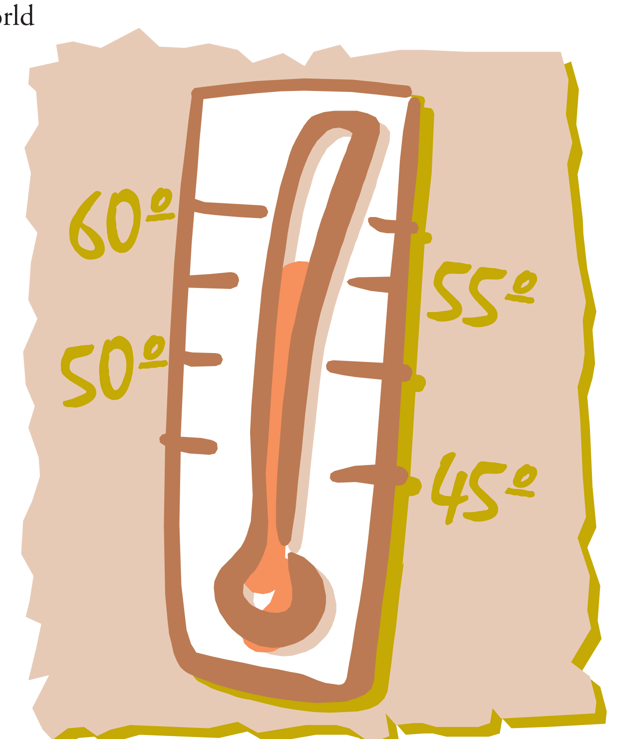
"The signal-to-noise problem that might exist in other parts of the world doesn't exist there," Overpeck told the roughly 100 workshop participants. He recalled a recent trip to the Arctic where he was awakened in his tent by the sounds of running water and chirping birds during the normally frozen spring. Sea ice has thinned by a quarter to half its original depth depending on location since submarines began measurements in the 1950s, he noted.

Such compelling evidence for global warming helped convince most of the world to support the Kyoto treaty, which went into effect last week with the support of 141 nations. The United States and Australia are the only industrialized countries that have not signed on to the pact to help slow the rate of global warming by reducing emissions of greenhouse gases like carbon dioxide.

It's somewhat more difficult to separate a long-term climate warming "signal" from the garden variety ups and downs ("noise") of natural climate variability in the mountainous western United States than in the Arctic. Temperatures drop at an average rate of about 3 degrees Fahrenheit for every 1,000-foot increase in altitude, making it more challenging to calculate averages. Too, the Southwest's semi-arid nature makes it a land of extremes, in rainfall as well as temperature.

Impacts of higher temperatures
Even so, the warming trend of recent decades appears to have spurred insect outbreaks in high-elevation southwestern forests, reported Thomas Swetnam, director of the UA Laboratory of Tree-Ring Research.

continued on page 53



Warming, continued

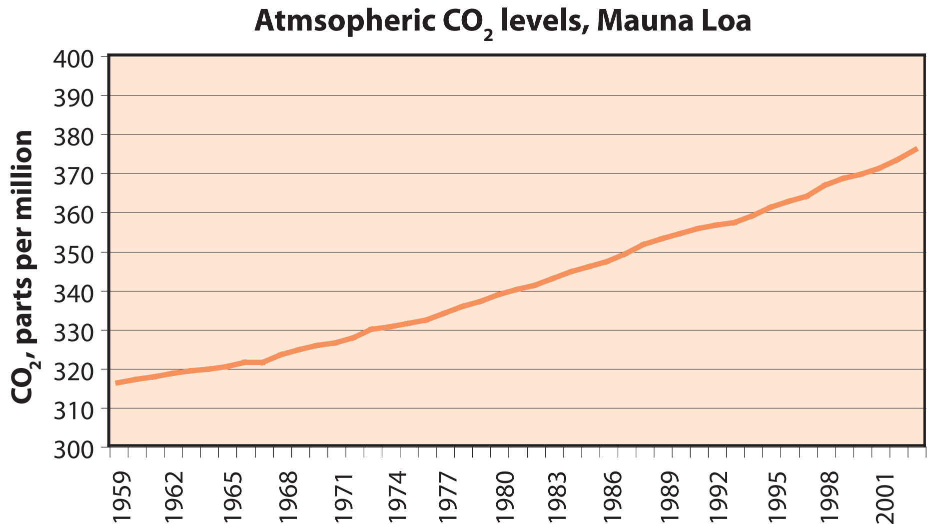
The variety of insects feasting on the spruce-fir forests atop Arizona's Mount Graham near Tucson included exotic maritime species that hadn't been seen in this region before, he noted. The dead trees then contributed volatile pitch and fuel to a fire last summer that burned to varying degrees about half of the spruce-fir forests there—the world's only habitat for the endangered Mount Graham red squirrel.

"The combined warmth and drought may be the real kicker here," Swetnam told the group. After also discussing recent increases in the scale of southwestern wildfires, he said, "Maybe we're at that point where we can say climate change is affecting the Southwest."

Unfortunately, high-elevation forests rarely host weather stations. One that does—the McNary station at 7,340 feet in elevation—shows a decrease since 1940 in the number of days without significant frost events, based on an analysis by U.S. Forest Service researcher Ann Lynch (Figure 2). Lynch, Swetnam and others consider these higher temperatures related to the severity of insect invasions of recent years.

Bark beetles damaged roughly four times as many acres of Arizona forests during peak outbreak years of the current drought compared to the 1950s drought. Airplane assessments tallied 1.9 million acres damaged in 2003, compared to 490,000 acres in 1957, according to data collected by U.S. Forest Service entomologist Roberta Fitzgibbons. (Another 860,000 acres were damaged in New Mexico in 2003.) The good news is the attacks on Arizona forests appear to have waned, she indicated, with a drop to 135,000 acres damaged statewide in 2004.

Meanwhile, about 18 million acres of Canadian forests were being ravaged, Swetnam noted. In addition, Canadian researchers have linked regional tem-



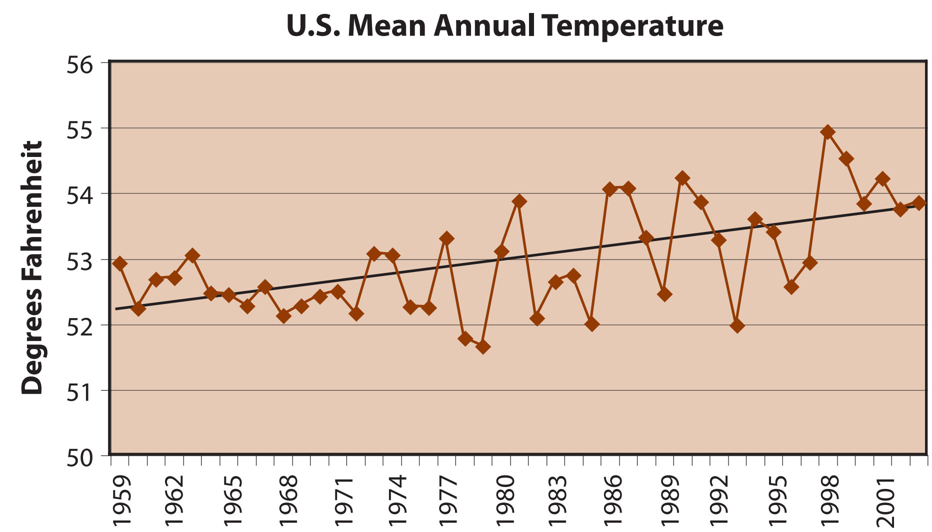


Figure 1. Carbon dioxide levels (top figure) as measured on the Hawaian island of Mauna Loa depict the ongoing rise of this greenhouse gas in the atmosphere. C.D. Keeling and his colleagues began collecting these measurements in 1958. Data for average annual temperature in the United States are also plotted for this same time period (bottom figure), with means estimated by the National Climatic Data Center based on available weather stations. As predicted, rising carbon dioxide rates are associated with rising temperatures, although other factors also are involved in the annual ups and downs. Source for carbon dioxide measurements: Keeling and Whorf data sets available at http://cdiac.esd.ornl.gov/ftp/trends/co2/maunaloa.co2. Source for U.S. temperature data set: http://www.ncdc.noaa.gov/oa/climate/research/cag3/cag3.html.

perature increases to acres-burned in recent wildfires, he said, citing research reported in the September 2004 issue of *Geophysical Research Letters.*

Western U.S. wildfires have also been on the rise as temperature climbs, although other factors come into play. For instance, the suppression of surface fires in Ponderosa pine forests promoted proliferation of seedlings and saplings, as did the harvesting of large trees. A wet period centered on the 1980s encouraged seedling and tree growth beyond what drought can support. On top of this, the carbon dioxide that enhances the Earth's natural greenhouse effect also serves as a fertilizer for trees and other plants.

As a result, many interior southwestern forests contain roughly twice the amount of biomass—i.e., the com-

continued on page 54

Warming, continued

bined dry weight of the living and dead vegetation—than would be expected given a natural fire regime, explained Ron Neilson, a U.S. Forest Service researcher based in Oregon who heads the Mapped Atmosphere-Plant-Soil System (MAPSS) project. Models he constructed with his colleagues suggest that only about one-eighth of the U.S. acreage that would naturally burn each year does so. Fire suppression thus encourages an unnatural build-up of biomass.

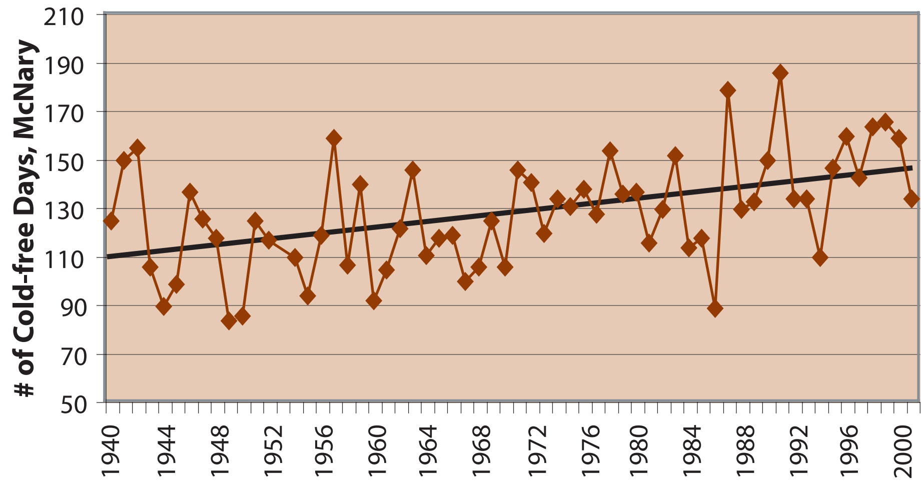


Figure 2. The length of time between frost events lasting more than a few hours in McNary, Arizona, has grown on average by roughly half a day each year, based on an analysis of daily temperatures by researcher Ann Lynch. This analysis excluded "isolated frost days," i.e., those with 10 frost-free days on either side. Source: Ann M. Lynch, research entomologist with the U.S. Department of Agriculture Forest Service Rocky Mountain Research Station in Flagstaff.

Managing dense forests

This "woodification" of forests, as some speakers called it, fuels the large-scale wildfires that have plagued the Southwest during dry years. For instance, the 2000 Cerro Grande fire around Los Alamos was the largest wildfire in New Mexico's history with about 47,000 acres burned. Two years later, the 2002 Rodeo-Chediski fire in northern Arizona's White Mountains burned about 460,000 acres, making it an order of magnitude larger than any other fire in Arizona's documented history.

Some forest managers, such as those in Arizona's White Mountains, are responding to the risk by thinning some of the smaller trees in the forests near residential communities.

"Going out there and thinning the wood is a good idea, but you're bucking the tide," Neilson told the group.

In addition to being a huge undertaking, thinning treatments are an expensive task. Few sawmills remain in the Southwest, except on tribal lands. This poses a dilemma for national and state forest managers trying to clear the smaller trees that increase fire risk yet yield little to no profit to loggers after transportation costs. As a result, the standard thinning rate for small-tree thinning treatments is $400 to $1,000 an acre.

Prescribed burning is also used by some forest managers, particularly on tribal lands, such as northern Arizona's Apache reservations, and in New Mexico's Gila National Forest. Although this technique can be more efficient than thinning when it works, air-quality restrictions and the high fuel build-ups can make this approach challenging to adopt and safely carry out in overgrown forests. The Cerro Grande fire started from a prescribed burn, for instance.

In addition to struggling to reduce fire risk near communities, land managers at the workshop worried about how global warming might impact ecological niches for various species. For example, some wonder whether the 1.9 million acres of southwestern pinyon pine devoured by beetles in 2003 will rebound into comparable pinyon-juniper stands, or be replaced by something else.

Invasive species and other colonizers

"A rapidly changing climate favors those species that can make rapid transitions," warned Kathryn Thomas of the U.S. Geological Survey's Southwest Biological Science Center. Following this logic, global warming might favor invasive species.

Thomas is just starting a five-year research project to document what's happening with invasives regionally. A survey of land managers found about half of them unsure whether "weeds" were increasing or decreasing, with the other half roughly split between the two options. More than 115 different alien invasive plants have been reported in the Southwest, and 88 of these thrive in woodlands, she said.

Ecologists and bioclimatologists agree that global warming would be expected to shuffle species around as their various habitats move north or south, or up or down a mountain. Neilson's modeling work, for example, points to large-scale expansion of woodlands at the expense of grasslands. For instance, live shrub oak and a variety of other species currently limited by frost could find their habitat had expanded up and over the Mogollon Rim.

Land managers are already reporting an ongoing "woody encroachment" of southwestern grasslands by mesquite trees and other woody plants. While woodlands expand into grasslands, grasslands could replace some southwestern deserts, according to Neilson's modeling results.

Land managers will face tough decisions about whether a plant is an invasive or

continued on page 55

Warming, continued

the rightful inhabitant of a new niche as the climate warms, Thomas and Neilson agreed.

"Do you protect the species that would be outcompeted in the Great Basin and hold that tide back? Or do you foster diversity—isn't diversity good?" Neilson asked.

Carbon dioxide fertilization

The influence of carbon dioxide on the plants themselves adds to the uncertainty about what the change will bring. The main greenhouse gas behind global warming, carbon dioxide (CO_2), is also an essential building block of plant tissue.

"There's no controversy over the fact that CO_2 levels are rising," noted Bruce Kimball, research leader at the U.S. Department of Agriculture's Maricopa facility between Phoenix and Tucson. "There would be some changes going on out there in natural ecosystems whether or not global warming was going on."

For decades, Kimball has been involved in testing how various plants respond to the increased rates of carbon dioxide in the atmosphere using an elaborate system of pipes and computers. The system maintains carbon dioxide levels in an open field at about 1½ times background levels. He and his colleagues have consistently found an increase in photosynthesis that translates into higher plant biomass.

Biomass typically increased by about 25 to 30 percent under the elevated carbon dioxide in woody species like cotton and grape, he noted, and by about 75 percent in sour orange trees.

In general, trees seem to respond better than grasses to elevated carbon dioxide rates, especially if precipitation rates increase, according to a 2004 *New Phytologist* paper Kimball recommended by Robert Novak and colleagues. This difference could be encouraging woody encroachment, although, again, other factors are involved.

Along with improving growth, elevated carbon dioxide levels improve a plant's water use efficiency. This factor could make a big difference in how the Southwest fares under climate change.

Output from Neilson's vegetation models considering potential niches for about 45 types of vegetation showed that the improvements in the water use efficiency rate as expected under rising carbon dioxide levels could dictate whether the U.S. West greens up or becomes more barren with global warming. The extent of the warming and potential changes in precipitation also would make a difference.

Immediacy in the message

Given the enormous risks at hand, one might ask why Americans, who as a nation produce a quarter of worldwide carbon dioxide emissions, won't sign on to an international effort to slow down the rate of global warming.

UA Environmental Psychology Professor Terry Daniel has a few hypotheses about why many people remain unconcerned. For instance, research indicates that in the human mind, "global" translates into "that's happening somewhere else." Meanwhile "Everybody is exposed," translates into "Nobody is exposed."

Also, scientists and society need to convey a specific course of action to take, not just report gloom and doom. It's difficult to be afraid of something abstract, and even more difficult to think about it if there's no solution in sight, he suggested.

When people understand global warming is happening in their own back yard, or affecting their favorite plant or animal or community, that's when they'll move to act, Daniel theorized. In short, if scientists want people to become concerned, they need to convince them that global warming is not a century away—it's here and now.

Melanie Lenart is a postdoctoral researcher with the Climate Assessment for the Southwest.

Resources on the Web

- The IPCC provides its reports and other background information at: http://www.ipcc.ch/index.html
- The National Climatic Data Center provides instrumental data at a variety of scales at: http://www.ncdc.noaa.gov/oa/climate/research/cag3/cag3.html
- To see how the current warming compares to 1,000-year temperature records reconstructed from tree rings and other archives, go to page 4 at the following link: http://www.ltrr.arizona.edu/trt/20040302.pdf
- Monthly data on atmospheric carbon dioxide measurements collected by Charles Keeling and colleagues since 1958 are available at: http://cdiac.esd.ornl.gov/ftp/trends/co2/maunaloa.co2
- For more on the Mapped Atmosphere-Plant-Soil System (MAPSS) project, see: http://www.fs.fed.us/pnw/corvallis/mdr/mapss/
- Also, a 12-page background document providing some MAPSS results is available at: http://www.fs.fed.us/pnw/pubs/science-update-6.pdf
- For more on Kathryn Thomas' invasive plant project, see the Southwest Exotic Plant Information Clearinghouse at the following website: http://www.usgs.nau.edu/SWEPIC/index.html

Nature's clock ringing in earlier springs

Plant and animal cycles show earlier and longer warm-weather seasons

by Melanie Lenart

Nature's biological clock measures time with the arrival of birds, the greening of leaves, and the budding of flowers. Now it seems the clock has sped up when it comes to spring's arrival, a leap that many view as a response to global warming.

"I have heard that the mayflower should now be called 'aprilflower' because it's switching its bloom time," said Elisabeth Beaubien, national coordinator of the Canadian program PlantWatch. Similarly, her research has shown quaking aspen trees, admired for their white bark and yellow fall leaves, are blooming about eight days earlier on average in Edmonton since the mid-1930s (*International Journal of Biometeorology*, August 2000). Aspen thrives in many U.S. states as well, although its bloom times in this country generally go unrecorded.

Concern over these changes in time, and the lack of a U.S. network to systematically monitor them, drew about three dozen scientists to Tucson for a late August workshop sponsored by the Institute for the Study of Planet Earth at The University of Arizona (UA) with funding support from five federal agencies. The group hopes to launch a nationwide monitoring project soon, explained workshop organizer Julio Betancourt of the U.S. Geological Survey and UA. "This is probably something we can get going by the next growing season," Betancourt said.

Co-organizer Mark Schwartz of the University of Wisconsin-Milwaukee has already set up a prototype website where anyone can sign up to submit their own national and regional observations (See sidebar on page 4).

Citizen networks

During the workshop, Beaubien and other program managers shared advice about setting up citizen networks to observe phenology, the timing of annual life cycle events. Although the word itself sounds unfamiliar to many people, the practice of phenology stretches back to the last ice age, Beaubien reported. She noted that ancestors of the Blackfoot tribe used the blooming of buffalo bean as a sign to hunt bison bulls.

In the Southwest, the monsoon's arrival has long been hailed as an opportunity for growth, by Hohokam farmers who planted beans and squash on floodplains thousands of years ago through modern-day gardeners who collect rain in barrels. But while climatological records pinpointing the monsoon's arrival show up in scientific literature and on the web, biological records documenting nature's response to seasonal climate events remain rare for this country.

One of these rare bloom records involves a lilac network launched in 1957 by Joseph Caprio of Montana State University, who also shared insights at the workshop. At its peak, more than 2,500 volunteers from 12 western states, were posting information on the location and blooming times for lilac shrubs. Caprio also distributed cloned honeysuckle bushes to a smaller group of volunteers. Dan Cayan of Scripps' Climate Research Division and colleagues including Caprio recently reported that the observations show lilac and honeysuckle flowers in the West were blooming 5 to 10 days earlier on average in the second half of the 1957–1994 record compared to the first half (*Bulletin of the American Meteorological Society*, March 2001). Unfortunately, the number of volunteers dropped precipitously since Caprio retired in the early 1990s.

In a more comprehensive study, Terry Root and her colleagues at Stanford University compared phenological records for 145 species including trees, insects, flowers, and birds from sites in Europe, Asia, and North America. They found that four out of five species examined had shifted their seasonal timing in a way that appeared related to temperature increases from human-influenced global warming (*Proceedings of the National Academy of Sciences*, May 2005). During the assessed time frame, which varied by species and record but averaged 28 years, the measured seasonal events for birds and trees shifted ahead about five days, while herbaceous plants like grasses and wildflowers were starting about two days earlier.

Although the earlier springs may sound good to snowbound northerners who see robins as a sign of pending release from winter's grip, these phenological shifts can signal problems ranging from earlier allergy attacks to potential missing links in the food chain.

Potential problems

An earlier start to the pollen season seems to be one consequence of warming temperatures, based on research in the Netherlands by Arnold van Vliet of Wageningen University and colleagues (*International Journal of Climatology*, November 2002). This should concern the roughly 15 percent of the

continued on page 57

Nature's clock, continued

population who suffer from hay fever, and could be problematic for those with asthma as well, noted van Vliet, who attended the workshop.

The Netherlands study also found trees were responding more rapidly than grasses, with juniper and oak releasing pollen nearly three weeks earlier in the 1990s than they had in the 1970s. In this case, that's good news for allergy sufferers, as grass pollens tend to aggravate allergies the most.

However, ecologists worry that disjointed shifts by different species could break food chain links and create other problems. Plants overall are responding more quickly to temperature than birds, and insects are reacting fastest of all, explained Jill Attenborough, program director of a project that collects phenology data from more than 21,000 regular observers in the United Kingdom.

"It helps people understand that the synchrony of the natural world is being threatened," Attenborough suggested. The U.K. network is supported by the efforts of The Woodland Trust, a nonprofit group that in 2000 joined efforts to recruit volunteer observers after identifying climate change as the single biggest threat to ancient forests.

Insect response

Scientists who studied insect outbreaks in southwestern forests have been working to document how warm temperatures contributed to recent attacks.

"The probability of outbreaks will increase as temperature increases because insects are cold-blooded," as Neil Cobb of Northern Arizona University explained during a water summit in Flagstaff last month. Freezing winter temperatures help keep insects in check.

Although drought clearly contributed to a recent bark beetle outbreak, entomologists suspect warmer-than-usual winter

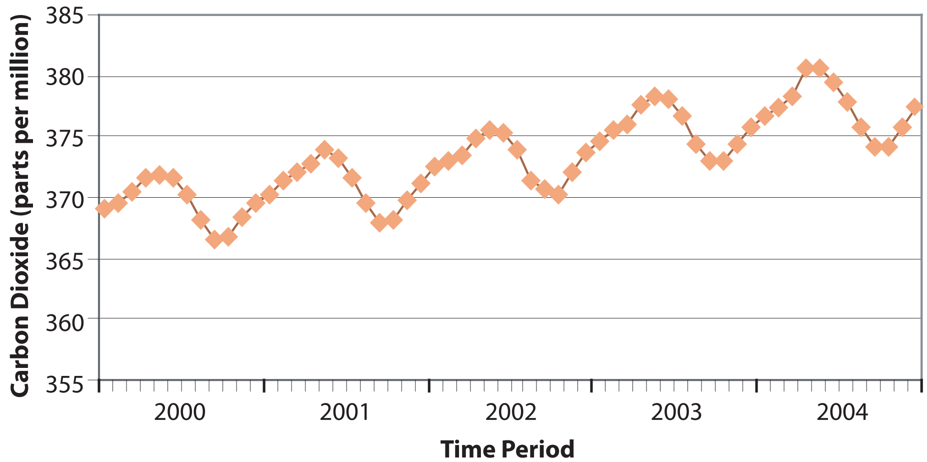


Figure 1. Carbon dioxide levels from Mauna Loa, Hawaii, fluctuate with northern hemispheric plant growth in spring and die-back in fall. Values for this atmospheric greenhouse gas are shown here by month based on data compiled by C.D. Keeling and T.P. Whorf.

temperatures may have influenced its scale. Beetles devastated about 2.7 million acres of southwestern pine forests from 2001 through 2004, according to estimates from the U.S. Forest Service's Southwestern Region.

Workshop participants were focused on the collection of phenology data to improve society's understanding of climate variablity as well as change. For many, the ultimate goal would be to produce more skillful climate forecasts and better predict response to climate swings.

"Basically we see phenology as an indicator of climate impacts, whether it's from natural variability or human-induced," van Vliet said. He noted that the latter includes the urban heat island effect that occurs as paved areas expand from city centers.

Temperature vs. rainfall

In the Southwest, plants often respond to rainfall variability more dramatically than to temperature, as the greening of the desert this past year dramatically demonstrated.

"Many of the showiest species require large amounts of rainfall when temperatures are cool but not cold," said Janice Bowers, a USGS researcher. Her research found the best wildflower years in the Sonoran Desert resulted when rainfall rates were about 50 percent higher than usual from September through March. What's more, these higher rainfall years tended to occur when the July–December index signaled an El Niño pattern was active in the tropical Pacific Ociean. (*Journal of the Torrey Botanical Society*, January 2005).

The El Niño this past year ushered in red brome, cheatgrass, and other invasive grasses that helped spark a record fire year in Arizona. As of September 15, most of the state's 725,903 acres impacted by fire this year burned in grasslands and grass-covered desert rather than forests, indicated Chuck Maxwell of the Southwest Coordination Center. (Meanwhile, only 23,097 acres burned in New Mexico.)

Rainfall certainly encouraged the extensive grass cover, but warmer spring temperature may help give invasive grasses a foothold over native species, some researchers suspect (*Southwest Climate Outlook*, February 2005). Unlike the more sparse cover of native wildflowers, a continuous grass cover can spread fire throughout desert ecosystems. Brushes with fire can be fatal to the Southwest's poster cactus, the saguaro.

continued on page 58

Nature's clock, continued

The phenology network actually could help battle the problem of invasive grasses leading fires into the saguaro's realm, noted Betancourt. For instance, a citizen network reporting the growing presence of buffelgrass could alert officials to take action, such as spraying herbicides before the grass consumed the landscape. Word of starthistle reaching the flowering stage could inspire officials to release a natural enemy like the yellow starthistle seedfly, he added. These actions could become more important as rising temperatures dry out grasses earlier in the season.

The longer warm weather seasons showing up in records could translate into longer and more severe fire seasons as soils once covered by snow face the harsh light of day for extended periods. The litany of problems this would bring includes the release of more carbon dioxide back into the atmosphere.

Carbon fluctuations

The dry mass of plants and trees amounts to about half carbon—all of it drawn at some point from carbon dioxide in the air. Because carbon dioxide is the main greenhouse gas implicated in the acceleration of global warming, its ups and downs affect the amount of heat the atmosphere retains at the Earth's surface. Northern hemisphere carbon dioxide levels rise and fall with the seasons as plants draw down this greenhouse gas in summer, then release much of it via decay when they die or drop their leaves in winter (Figure 1).

Like much plant growth itself, the seasonal timing of the carbon dioxide "drawdown" had shifted forward by up to a week as of the mid-1990s compared to the early 1970s, as reported by a longtime carbon dioxide recordkeeper, the late Charles Keeling, and colleagues (*Nature*, July 11, 1996). In a follow-up paper, Keeling, lead author Ranga Myneni of Boston University, and others found satellite evidence to support their argument that this carbon dioxide shift reflected increased plant growth during a longer growing season (*Nature*, April 17, 1997). They estimated that the northern growing season increased by roughly 12 days between 1982 and 1990, with two-thirds of the change attributed to an early spring and the remainder from a delayed autumn.

The opportunity to calibrate satellite "green-up" imagery with documented on-the-ground leafing out was touted as another important reason for a continental-scale phenology network in this country. More of these comparisons will help scientists understand how organisms that form the planet's biosphere are responding to climate variability and change.

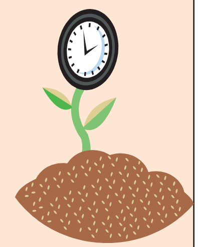
With more than 150 countries and a growing number of U.S. states vowing to reduce the input of carbon dioxide into the atmosphere, the helpful role of plants is destined to receive much attention by those trying to monitor the year-to-year changes in the carbon cycle. The implications for global warming go beyond carbon dioxide dynamics, as vegetation cover can also increase the Earth's retention of direct solar radiation, especially when compared to snow cover.

In addition, farmers, ranchers, tourists, doctors, teachers, biologists, journalists, gardeners, land managers, and many other members of society also stand to benefit from continental-scale information linking climate fluctuations to the seasonal cycles of plants and animals, participants pointed out. With so many potential beneficiaries, the message from the workshop rang out loud and clear: It's time for U.S. residents to synchronize their watches and clock nature's biological cycles.

Melanie Lenart is a postdoctoral research associate with the Climate Assessment for the Southwest (CLIMAS). The SWCO feature article archive can be accessed at the following link: http://www.ispe.arizona.edu/climas/forecasts/swarticles.html

Observing nature's clock

By Melanie Lenart



Workshop planners and others are working to set up phenology observation sites at select weather stations and long-term ecological research sites, as well as citizen observer networks. Although a national phenology network is still evolving, opportunities exist to contribute information on a national and international level:

USA National Phenology Network
http://www.uwm.edu/Dept/Geography/npn/
Allows observers to contribute sightings of seasonal events.

Sonoran Desert Phenology Network
Contact: crimmins@u.arizona.edu
UA extension specialist Michael Crimmins and other UA researchers are working to develop phenology protocol for plants in the National Park Service's Sonoran Desert Network. Citizen observers can volunteer.

Project FeederWatch
http://www.birds.cornell.edu/pfw/
A national phenology effort for birdwatchers

GLOBE Program
http://www.globe.gov/globe_flash.html
Hands-on scientific endeavors for students including the collection of phenology data

Canadian NatureWatch
http://www.naturewatch.ca/english/

European Nature's Calendar
http://www.dow.wau.nl/msa/epn/index.asp

U.K. Phenology Network
http://www.phenology.org.uk/

Grassland dynamics shift with climate fluctuations

By Melanie Lenart

As the drought deepened, ranchers and others at a January workshop brainstormed ways to keep southwestern grasslands resilient despite rising temperatures and pendulum-like swings in rainfall.

"I make my living when it rains," rancher Dennis Moroney of the CrossU Cattle Company told the group of about 130 ranchers, range managers, and natural resources specialists gathered for the two-day Climate and Rangeland workshop and Society for Range Management (SRM) meeting held near San Carlos, Arizona. "Last spring I said, 'If this is global warming, I'll take it.' I'm not so sure today,"said Moroney.

Plentiful rainfall during the winter and usually bone-dry southwestern spring in 2004–2005 put a dent in the drought that has plagued Arizona and New Mexico since at least 1998, but a dearth of rainfall since October has plunged much of the Southwest back into drought over the last few months. On the first day of the January 25 workshop, Phoenix had not received a drop of rain in 98 days, and Tucson had only received about 0.1 inches during that same period. Meanwhile, northern Arizona was still without snowpack.

"As we left town, we were getting our first significant snowfall of the year," noted Northern Arizona University (NAU) Professor George Koch, who drove up from Flagstaff on the morning of January 26. "This is shaping up to be the driest winter since the driest winter a couple of years ago," he added. On February 7, Flagstaff's National Weather Service office announced that the 2.49 inches of precipitation received between September 1 and February 6 represented a new record low in 109 years.

Gregg Garfin, program manager for the University of Arizona's (UA) Climate Assessment for the Southwest (CLIMAS), noted that El Niño exerts a tremendous influence on regional winter precipitation tallies. When El Niño reigns, sea surface temperatures run higher than average in the eastern Pacific Ocean. Often this helps pull jet stream moisture down to this region for the winter and sometimes through the spring, as it did last year. But things have changed.

"This winter's temperatures in the eastern Pacific, although not officially a La Niña, are cooler than average. We think that's what initiating this dry episode," Garfin told the group. Conditions officially met National Oceanic and Atmospheric Administration standards for a La Niña event the following week, after eastern Pacific sea surface temperatures had remained cooler than average for the required three months. This suggests the drought is likely to continue through the winter at least, Garfin indicated.

Garfin had worse news to convey. He is among the climatologists who suspect that a related influence commonly known as the Pacific Decadal Oscillation (PDO) switched in the late 1990s into a phase that spells long-term drought for the Southwest. While El Niño works at the seasonal scale with phases that typically last only a year or two, the PDO can stay in one phase for 20 years or more.

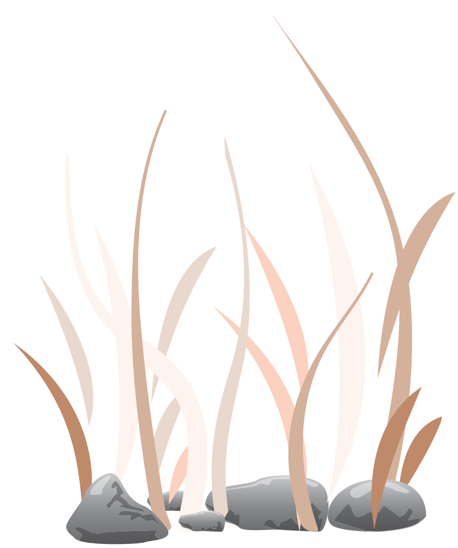
El Niño variations represent one of three processes influencing PDO phases, Garfin told the group, referring to research by Niklas Schneider and Bruce Cornuelle (*Journal of Climate*, November 2005). The other two influences are the Aleutian low, an atmospheric measure of sea level pressure that fluctuates much faster than El Niño; and the Kuroshio-Oyashio Extension, an ocean current that responds to El Niño phases but fluctuates much more slowly. At this point, skill in predicting the influences affecting the PDO is limited to a few years, the authors indicated in their paper.

Global warming's influence falls on top of fluctuations of El Niño, the PDO and other climate patterns. It launches a relatively predictable rise in temperatures accompanied by largely unpredictable changes in precipitation patterns. Following the ongoing trend for increasing temperatures, globally 2005 registered as the hottest or second-hottest year on record, depending on the analytical method used.

In time, the Southwest might experience more heat waves and record-breaking highs and fewer frost days, Garfin explained, citing a research paper by Noah Diffenbaugh and others (*Proceedings of the National Academy of Sciences*, November 2005).) Precipitation is also likely to become more extreme, in effect featuring more droughts and floods as the water cycle speeds up along with evaporation rates.

Grassland thresholds

The one-two combination of rising temperatures and more drought can really impact grasslands and other ecosystems. Grasslands rank among the most sensitive ecosystems to climate fluctuations,



continued on page 60

Grassland dynamics, continued

whether from natural variability or climate change.

"We're working with an ecosystem that has very quick responses to climate variability," noted Michael Crimmins, a UA Cooperative Extension climatologist who helped organize the workshop along with others from cooperative extension, CLIMAS, and SRM. Climate influences act along with past management actions, soil type, competition between species, and environmental disturbances, he added. "These increasing temperatures, even if precipitation remains the same, are going to change things."

Changes in climate can push a grassland system over a "threshold" into a new state, NAU Professor Thomas Sisk said. He showed an image of an idealized conceptualization of thresholds (Figure 1). A ball resting in the bottom of a pit represents one ecosystem state. Drought, global warming, or related disturbances can metaphorically lift the ball out of this "steady state" and shift it up and over the edge of a threshold into an entirely different steady state.

"Where are those thresholds? That's sort of the $64,000 question," Sisk told the group. "It's chaotic, unpredictable. That's why we're here today."

Protecting grasslands

Sisk is working with the Diablo Trust, a collaborative rangeland management group in northern Arizona, to monitor how selected plots respond to different grazing approaches. Monitoring involves keeping track of rangeland conditions by systematically measuring variables such as soil moisture and the percentage of desirable vs. undesirable plants within a specific area. This can help ranchers understand when they are risking a threshold change.

Ranchers may need to remove some grazing animals from shriveling grasslands during times of drought, Sisk noted, with or without a dictate from the government agencies that issue grazing permits. Often, people have a tendency to "wait, hope, and pray" rather than reduce livestock numbers, he observed.

"If it's really late, or we pray for a really long time, then we may cross that threshold," he added. The field of decision theory weighs the costs of changing management against the risks of inaction or of making a bad decision. In an acknowledgement of the difficulty in making decisions based on an uncertain future, Sisk noted that the best decision sometimes can be to wait out a dry spell—if it does rain in time to save the ranch.

"The response when it rains is phenomenal," said Moroney, whose ranch in McNeal reacts rapidly to rain, like most southwestern grasslands. "You see change take place in three or four days."

Summer rains can make or break a rancher's fiscal year. Yet the success of climate predictions for southwestern summer rainfall—largely dependent on the monsoon circulation that drives in the rain—lags far behind the skill in forecasting winter precipitation, mainly because of El Niño's influence on the latter. Arizona state climatologist Andrew Ellis, though, has found that late monsoons often equate to weak monsoons (*International Journal of Climatology*, February 2004). The 2005 monsoon fit the bill on both counts.

The larger spatial coverage of winter storms eases predictability, Crimmins explained. Winter storms often extend across the state for several days, he indicated, while summer thunderstorms pop up almost randomly over small areas.

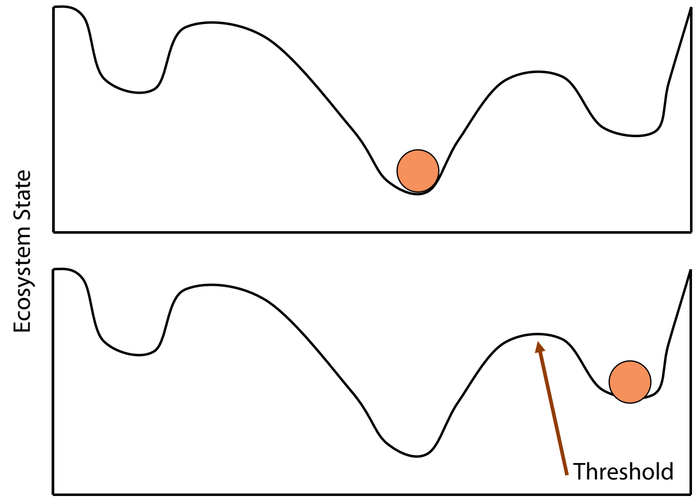


Figure 1. Grasslands and other ecosystems have "thresholds" relevant to specific states, such as forage production. Changes in climate can theoretically shift the grassland from one stable state (top) into a different stable state (bottom). Once the system has passed the threshold, it is difficult for it to return to its pre-existing state. Source: Thomas Sisk, NAU.

During years when the monsoon falters and sputters, like last summer, ranchers face a tough decision about whether to buy feed while hoping for rain, seek out greener pastures for a few months, or prematurely sell some of their carefully bred herd. If large-scale drought leads ranchers to flood the market with cattle, prices will drop for everybody.

A greener pasture

"Grass banking" can help ease the risk of running out of forage before the calves are fatted. For instance, a group of ranchers might set aside a common field for times of trouble, or individual ranchers can use their own land in ways that lessen the impact of grazing in any one spot, Moroney suggested.

"I moved my cows 11 times last year. We do that to shorten up the amount of time they spend in a pasture," he said. "Then we're always feeling pretty good that we have feed ahead of us and

continued on page 61

Grassland dynamics, continued

behind us in case rain doesn't come through."

He noted that he favors pastures with mesquite trees—generally considered undesirable by ranchers—during the season when dangling bean pods serve as a protein supplement for cows.

Moroney also suggested that adaptive management ideas could include putting cattle out in the desert when grasses encroach, as they did in 2005. The spread of grasses into the desert during last year's plentiful spring rains caused trouble. The grasses quickly cured into fuel for summer fires that sparked a record number of acres burned in Arizona. A quarter of a million of these acres burned outside Phoenix in the Cave Creek Complex fire, killing many of the Sonoran Desert's signature cactus, the saguaro.

Fire in grasslands

While fire spells disaster for saguaros, it can help grasslands win the competition against other woody plants like juniper, mesquite, and creosote.

Grasses "expressed themselves dramatically" after Moroney worked with the Natural Resource Conservation Service to fight off mesquite trees by spraying several hundred acres with herbicides. In recent decades, mesquite trees have been invading his ranch, along with grasslands throughout the Southwest. But the chemical treatments cost too much and are fairly ineffective without a follow-up by fire, he said, so the plan is to conduct some prescribed burns to further control the mesquite invasion.

The proper fire regime can maintain grasslands facing invasions from woody plants such as juniper as well, UA Professor Steven Archer told the group.

Based on research about how long it takes juniper to establish and grow in similar Texas and Oklahoma grasslands, ranchers need to have a fire at least every 10 years to keep juniper off highly productive, non-grazed landscapes, Archer reported. On grazed sites, the window of opportunity to prevent juniper encroachment can shorten to five years, he explained. His research has shown that cattle grazing can help woody plants invade by removing the grasses, known as fine fuels, needed to carry fires capable of suppressing trees and shrubs. Less productive sites or more heavily grazed sites may need to be burned even more often because the sparser ground cover translates to reduced fuel loads and hence patchier fires with lower intensities, he indicated.

Other factors

Drought, global warming, fire, and woody plant encroachment all can change grassland dynamics. So can invasive grasses and weeds, insects, and carbon dioxide. Grassland insect invasions often track the ups and downs of rainfall. Invasive plants, too, can respond to plentiful rainfall, as Sahara mustard and red brome did when colonizing desert lands last spring.

The greenhouse gas carbon dioxide, responsible for about 60 percent of the ongoing warming, also affects invasive plants, insects, and other factors influencing rangelands dynamics. For instance, woody plants such as trees and shrubs tend to grow more quickly than grasses in experiments exposing them to the carbon dioxide levels expected by about mid-century. Desert landscapes have undergone "reverse desertification" when exposed to these elevated levels of carbon dioxide, with 40 to 50 percent increases in productivity, Sisk pointed out. (For more information, see the 2004 review paper by Robert Nowak and colleague in *New Phytologist*.)

Even among grasses, the extra carbon dioxide in the air will favor some species more than others. It provides a bigger boost to plants that use the "C3" pathway to photosynthesize, such as trees and many cool-season grasses including bromes and cheatgrass. So-called C4 plants, which include most warm-season grasses and invasive species like lovegrass and buffelgrass, are not as affected.

The rising levels of carbon dioxide offer a high note that may interest farmers as well as ranchers: Most crops are C3 species, while most "nasty weeds" are C4 species, Sisk noted. However, there's also some evidence that insects need to eat more when dining on plants grown under higher carbon dioxide levels.

Increasing resiliency

A growing list of disturbances join drought in impacting grasslands. Grassland dynamics are likely to become more complex with the changing climate and related factors, increasing the risk of crossing a vegetation threshold, with major shifts in the species composition and productivity of rangelands.

Although rancher Richard Collins mentioned he was having a difficult time maintaining his natural optimism when faced with the workshop news, Garfin compared the growing understanding of the climate risks facing grassland managers to the awareness that had grown in Louisiana over the past couple of decades that a major hurricane could devastate New Orleans.

"We did not reduce vulnerability and increase resilience," Garfin noted. "And I think that's the task. We've got the information. The challenge is to take climate change information … and try to translate that into something that converts into a real and practical management plan."

Melanie Lenart is a postdoctoral research associate with the Climate Assessment for the Southwest (CLIMAS). The SWCO feature article archive can be accessed at: http://www.ispe.arizona.edu/ climas/ forecasts/swarticles.html

Rising temperatures bump up risk of wildfires

Global warming adds firefighting challenges in both forest and desert

BY MELANIE LENART

The Grand One looks doomed. The world's largest recorded saguaro, it stood its ground on a hillside near Phoenix while last year's Cave Creek Complex fire raced through on knee-high grasses and, worse, lingered in nearby shrubs. Now yellow lines radiate up several of its roughly dozen arms as the magnitude of the event sinks in (Figure 1).

It may soon join the list of casualties from wildfire—a list expected to grow longer with the days of summer as the southwestern climate continues to warm. The input of greenhouse gases mainly from burning oil, coal, and gas has temperatures on the upswing around the globe, including the southwestern United States.

The ancient saguaro looks worse than it did even a few months before, range and watershed specialist Carol Engle said on a day in late March. Now she has doubts about whether it will pull through, as she and many others had been hoping. She pointed out splits where insects could penetrate its massive trunk, larger than a refrigerator at the base. Between the trunk and an arm, bubbles of black char look like a belated attempt to form protective bark. Or, to use Engle's analogy, like a marshmallow that's toasted for too long.

Singed during a record Arizona fire year that burned more than 700,000 acres in 2005, The Grand One could serve as a poster illustration about how wildfires could worsen with global warming and related changes. 2005 nearly tied 1998's record for world's warmest year since instrumental records became relatively reliable in the late nineteenth century. While the fire raged, Phoenix set its own record lows for humidity and highs for temperatures.

When it's hot

Climbing temperatures are expected to bring more raging infernos, in desert, grasslands, and forests alike—and the homes constructed among them. The 47,000 acre forest fire around Los Alamos, New Mexico ruined about 260 homes and required the evacuation of about 20,000 people in 2000. The 468,000 acre Rodeo-Chediski forest fire in northern Arizona destroyed about 400 homes and forced 30,000 people to evacuate in 2002.

In both cases, high temperature extremes in the three months leading up to the fire ranked right up there with low precipitation extremes (Table 1).

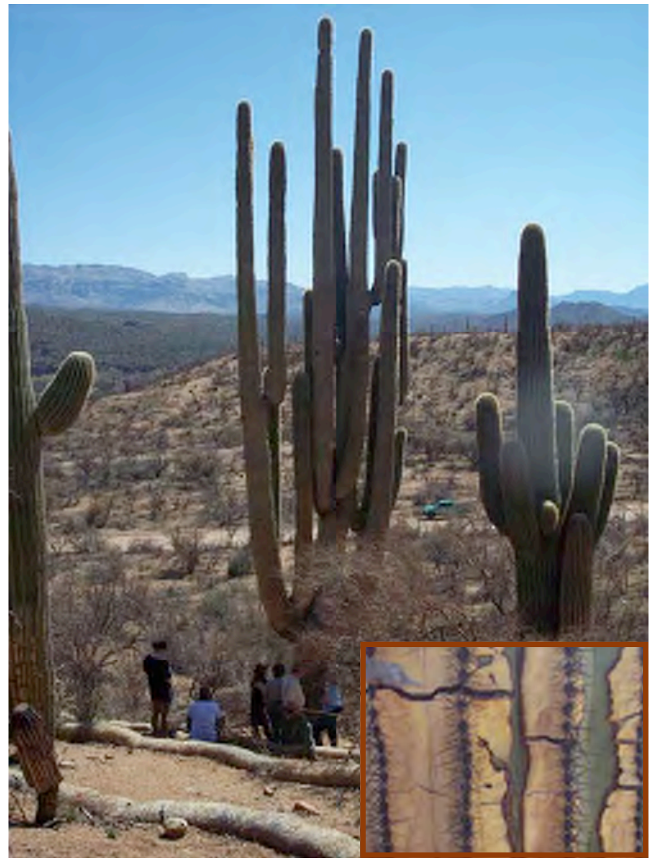


Figure 1. The world's largest recorded saguaro was damaged last year during a fire near Phoenix, Arizona. The lower righthand inset shows a close up of the fire damage. Source: Stephanie Doster, Institute for the Study of Planet Earth

Firefighters managed to shield homes in the Scottsdale area of Phoenix from the 248,000 acre Cave Creek Complex fire, which torched about two-thirds of the 50,000 acres of Sonoran Desert that burned in 2005. This important ecosystem features the saguaro cactuses (*Carnegiea giganetea*) exclusive to the southwestern United States and northern Mexico.

Some researchers suspect warming temperatures and an early spring are aiding and abetting the invasive grasses that helped carry last year's fires into saguaro territory (*Southwest Climate Outlook*, April 2005). Although native grasses and wildflowers can also carry fire following rainy winters, their clumpy, uneven cover proves less efficient at carrying fire than an even, continuous cover of monocultural grasses.

After wet winters like 2005, even normal southwestern temperatures in May and June soon convert invasive and native grasses alike into what firefighters call "fine fuels"—dried-out stalks that feed a surface fire.

Tonto National Forest fire manager Gary Daniel provided an example of how temperatures affect fine fuels, referring to his work on prescribed burns. If grasses remain moist after the cool of evening, he and his crew had an easy solution: "We just let the sun beat on it a little more, let the ambient air temperature dry out, and we're ready," Daniel recalled. "An hour in full sunlight would have a tendency to dry that grass out."

continued on page 63

Wildfire risk, continued

Forest drying

In the forest, it takes about 40 hot, dry days (roughly a thousand hours) to convert fallen branches on the forest floor into flammable material that will magnify a fire's heat—perhaps enough to ignite live saplings. These saplings, in turn, can become ladders to lift the flames into the crowns of established trees. Branches and logs from three to six inches in diameter are the "thousand-hour fuels" that firefighters worry about when gauging forest fire danger and evaluating whether a surface fire might transform into a crown fire.

Woody materials are likely to remain dry longer as the climate warms, Timothy Brown of the Desert Research Institute in Nevada and colleagues projected, based on the expected impact of warmer temperatures and their influence on relative humidity (*Climatic Change*, January 2004). Their modeling experiment focused on forests, comparing conditions for two decades through 1996 to those projected for two decades through 2089 using a global warming scenario.

"The key thing was an increase in the number of days of high fire danger," Brown said. "We basically found throughout the West that the number of days increased by about two to three weeks."

In another analysis, of 11 western states, New Mexico and Arizona were among the most sensitive to temperature effects on the annual "area-burned"—the amount of land crossed by fire in a given year. U.S. Forest Service researcher Donald McKenzie and colleagues found higher temperatures led to a "sharp increase" in area-burned in the historical record, using data for the years 1916 through 2002 (*Conservation Biology*, August 2004). New Mexico's annual area-burned fluctuates with spring temperatures in particular, the analysis by McKenzie and colleagues showed.

Similarly, research by The University of Arizona's Michael Crimmins and Andrew Comrie found low-elevation fires in southern Arizona increased during warm springs when they followed wet winters (*International Journal of Wildland Fire*, 2004).

The results fit the pattern for the Southwest fire season to start during the dry days of May and June and end within weeks of the summer's monsoon season arrival, usually in July. It also sparks concern for those anticipating the continuation of global warming, as spring temperatures in New Mexico and Arizona are rising as are temperatures in other seasons (Figure 2).

It's the heat *and* humidity

Temperature has an established link with fire danger on several fronts. Fires light more readily when the sun is beating down and raising daily temperatures. Lightning bolts fly more often with higher temperatures, too, providing more opportunities for fire ignitions. And fires can spin out of control more easily when overlying air is warm, especially in the absence of cool nights that help the fire to "lay down."

Fire event	Temperature rank (highest)	Precipitation rank (lowest)	State
Los Alamos (2000)	2	1	New Mexico
Rodeo-Chediski (2002)	4	3	Arizona
Hayman (2002)	12	2	Colorado
Biscuit (2002)	17	15	Oregon

Table 1. While seasonal precipitation tended to rank among the lowest during three months leading up to major western fires, temperatures tended to rank among the highest. Climate records go back to 1895. Source: Data from Western Regional Climate Center.

Some of these factors combined in 2005 in the Phoenix-area Cave Creek Complex fire, the union of several lightning-started fires. Local daytime temperatures in the "hundred and teens" and relative humidity levels that dipped as low as 2 percent turned the grass-invaded desert into a sea of flames, reported Jeff Whitney, a natural resource manager who helped battle the blaze. Even at night, relative humidity only rose to about 9 percent, well within the 20 percent range that firefighters peg as dangerous.

"We've usually got a better opportunity to work on suppressing the fire at night," Whitney said. "But we didn't have those conditions during the Cave Creek Complex—it burned through the night."

Air temperature wields an important effect on relative humidity. Hot air can hold more moisture than cool air, which is partly why higher daytime temperatures are linked to higher evaporation rates. Conversely, when air cools during the night, its relative humidity increases, sometimes to the point of saturation. If the air drops down to the "dewpoint temperature" some of the moisture it contains will condense into dew, fog, or some other form of precipitation.

Whether moisture condenses or not, higher relative humidity levels reduce fire danger, Daniel noted.

"In the evening, temperatures will go down and the humidity levels will start to increase again. We call it a recovery. If we have not much of a recovery at all at night, we can have active burning during the night and this can also make it worse the next day," he said.

Both global warming and the urban heat island effect tend to boost nighttime temperatures more than daytime temperatures. That's because greenhouse

continued on page 64

Wildfire risk, continued

gases and concrete both absorb solar radiation. After a long day of solar heating, they release some of the energy they've collected as infrared radiation—i.e., heat. This is most noticeable at night, once the sun's direct rays are out of the picture.

Hot air

Warm air tends to be more "unstable" than cool air in a meteorological sense, too, explained Charles Maxwell, fire weather program manager for the Southwest Coordination Center.

"If you have warmer surface temperatures, the atmosphere is more unstable. That's more conducive to strong convection and to blow-up fires" like the Rodeo-Chediski, Maxwell said. "Instead of having a fire driven by the wind and environment, the fire becomes a lot more powerful and controls the environment and dictates the weather. It's very similar to a thunderstorm, the way it works," Maxwell said.

A warm surface, whether caused by a fire or a mountainside baking in the hot summer sun, will lift air parcels up into the atmosphere. A fire tends to do so faster, which adds to the instability. The ascent of these air parcels leaves a void that surrounding air quickly moves to fill. These winds further fan the flames.

As with thunderstorms, the air parcels uplifted by fires often become clouds as they rise and cool. These clouds, known as pyrocumulus, contain moisture they extracted from fuel, soil, and especially living trees, Maxwell noted.

Alex McCord, a longtime Arizona Division of Emergency Management hazards officer, elaborated on this, noting that combustion also contributes moisture by converting stored carbohydrates in trees back into carbon dioxide and water.

"Even if it's bone dry, there's moisture in the wood," McCord said. When this

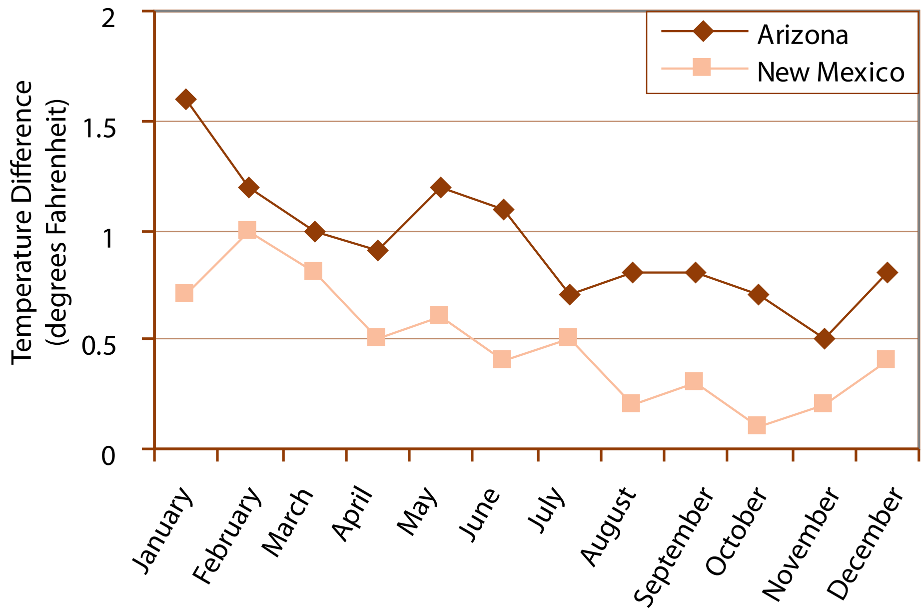


Figure 2. The difference between Arizona and New Mexico's average monthly temperatures in the past five years (2000–2005) compared to the full record (1895–2005) is shown above. The difference was most pronounced in winter and spring. Data: Western Regional Climate Center.

wood "blows up" into the clouds, it can form raindrops. "It used to be wood but now it's rain," he added.

Like the updrafts that helped form the clouds, downdrafts can accompany pyrocumulus rainfall. These sudden, erratic winds further vex firefighters by spreading flames in unpredictable directions.

Warmer air also tends to increase the incidence of lightning, which causes about 80 percent of the fire starts in the West. However, lightning strikes remain relatively unpredictable despite their importance in igniting western wildfires.

The fuel factor

Seasonally, fire danger fluctuates with the moisture condition of grasses and downed wood, respectively known as fine and heavy fuels in firefighter parlance. At longer time scales, explosive growth of saplings makes southwestern forests more prone to large-scale crown fires (*Southwest Climate Outlook*, February 2005).

"A lot of our landscapes are primed," as Whitney observed. Like many fire managers and historians, he noted that ongoing efforts to smother most blazes as upstarts means the ones that do manage to mature generally have loads of material to fuel their flames. Nationwide, only about an eighth of the acreage that would naturally burn each year typically escapes suppression efforts, according to an analysis by U.S. Forest Service researcher Ron Neilson and others.

The bark beetles and drought that killed millions of pines in recent years appear to have contributed to reducing fire risk—at least temporarily—by reducing the amount of flammable foliage in the forest. At an August 2005 water summit in Flagstaff, Northern Arizona University researcher Neil Cobb reported that the ponderosa and pinyon that had succumbed to bark beetles in 2003 and 2004 retained only about 13 percent of their needles, on average.

"If you don't have a canopy—all you have is dead sticks sitting up there—you probably decrease the risk of catastrophic crown fires," Cobb told

continued on page 65

Wildfire risk, continued

the group. However, once the beetle-killed trees start falling to the ground, their wood will join the thousand-hour fuels that can potentially ignite future conflagrations.

Management efforts to thin forest stands or clear out invasive grasses can reduce fire danger locally. Tree-thinning projects in forests in Arizona's White Mountains and Flagstaff reduce fire hazards in sections of pine forest. Not surprisingly, efforts focus on areas where forests border communities.

However, climate variability and change also influences fuel build-up to an extent that makes it difficult for people to reduce fire danger on the regional scale without allowing a return to the natural fire regime. Global warming is likely to increase climate variability, with larger swings from wet to dry and back again. Some project global warming will increase the magnitude of events associated with El Niño and La Niña (*Southwest Climate Outlook*, January 2006).

Records compiled from historic observations, tree rings, and charcoal deposits all indicate large climate swings boost the potential for severe fires in highland forests. Wet periods encourage abundant growth in forests—many small trees pop up to celebrate the moisture. This increases the risk of stand-level drought during dry periods that follow, with a multitude of tree stems drawing from the same pool, like too many straws in a drink.

Back in the desert

In lowland systems like grasslands and desert, wildflowers and grasses tend to flourish following above-average winter rainfall, which typically coincides with El Niño events, U.S. Geological Survey researcher Janice Bowers has found (*Southwest Climate Outlook*, September 2005). Ironically, this often increases fire danger because grasses soon dry out to become fuel loads.

Evidence indicates some invasive grasses can load conditions even more than native grasses. For instance, the invasive buffelgrass yields a longer-lasting fuel than many native grasses. Buffelgrass is sensitive to winter lows, so the warmer temperatures that come with global warming may be encouraging its spread.

Another invasive grass, red brome, appears to gain a stronger foothold based on an aspect of global warming— higher carbon dioxide levels. Rising atmospheric carbon dioxide levels account for about 60 percent of the modern warming. They also tend to boost plant growth, favoring some plants more than others.

In one experiment considering the effect of futuristic carbon dioxide levels, red brome grew 50 percent bigger and more dense on average than three native grasses found in the Sonoran Desert (*Nature*, November 2000). Atmospheric carbon dioxide levels in the experiment were roughly double the pre-industrial level of 280 parts per million, while today's levels are about one-third higher than pre-industrial levels.

An invasion of red brome helped carry fire into the desert areas torched by the Cave Creek Complex fire last year. During a March visit to a 30-degree slope that tapers down to the Verde River, the desert area touched by the fire was sprouting flowers again.

From afar, the classic Sonoran Desert landscape looked less damaged than the charred oak scrub nearby. But up close, many of the cactuses looked scarred. Past experience indicates that many of the saguaros straddling this steep slope could take another five years before they realize they're dead, researchers indicate.

Research on the effects of fires in saguaro territory remains limited, so it's unclear exactly what it would take to bring this system down. However, fire has a well-documented role in promoting grasslands over woody plants like juniper and mesquite (*Southwest Climate Outlook*, February 2006). Saguaros are also woody plants, as their ribbed remains on the desert floor indicate.

Some vegetation models of global warming effects predict grasslands will encroach upon major expanses of southwestern desert, given an increase in precipitation as well as temperature. For instance, in one climate change scenario considered by the Mapped Atmosphere-Plant-Soil System project, a rise in average temperature of 12 degree Fahrenheit with an increase of average precipitation of 22 percent in the model led to grasslands taking over deserts in most of southern Arizona and some of southern New Mexico (*Pacific Northwest Research Station Science Update*, January 2004).

The Sonoran Desert may be starting to head in that direction already, if 2005 is any indication of what warmer temperatures will bring during wet years. With help from invasive grasses, wildfires can fly across low-elevation grasslands and even deserts, as during this record-setting year in Arizona. Meanwhile, warmer temperatures during dry years can help set the high-elevation forests ablaze. Dense thickets of saplings can feed the conflagrations, as in the Rodeo-Chediski and Los Alamos fires.

Management efforts to defuse forests through thinning projects and protect deserts by weeding grasses and shrubs around saguaros can help. But unless there's a quantum leap in the number of acres treated through such efforts, southwesterners should brace themselves for longer, potentially severe fire seasons in years to come as the climate continues to warm.

Melanie Lenart is a postdoctoral research associate with the Climate Assessment for the Southwest (CLIMAS). The SWCO feature article archive can be accessed at the following link: http://www.ispe.arizona.edu/climas/forecasts/swarticles.html

Seeking Sustainability

Seeking Sustainability Foreword

By Barbara J. Morehouse

Global warming poses enough challenges to keep decision makers and resource managers in the Southwest busy for decades to come. Some of these challenges already qualify as serious and immediate problems, wildfire threat in the region's forests being one of the most compelling. The specter of more frequent, more intense, and longer-lasting drought casts a shadow over ebullient plans for old-style, resource-intensive development even as housing developments, retail centers, tourist facilities and businesses spread ever more widely over the landscape.

It's not surprising, under these circumstances, that sustainability has again emerged in public discourse as a guiding vision for maintaining interconnected viability in economic, societal, and ecological systems well into the future. The public's notion of sustainability, however, continues to be weighted with definitions that confound its mobilization in decision processes. Especially problematical is the tendency to associate sustainability with maintaining status quo conditions.

The concepts of resilience and transformation provide a useful alternative for addressing the complex problems that global warming is likely to pose for coupled human-natural systems. Resilience is the capacity of a system to absorb perturbations and to reorganize in response to changes in a manner that sustains the essential integrity of its function, structure, identity, and feedbacks. Transformation, by contrast, occurs when a system loses its viability in response to overwhelming disturbance and changes into a fundamentally new system. Tough decisions lie ahead about when, where and under what circumstances to manage for resilience or to invest in transformation. The chapters in this section illustrate some of the ways in which people are already exploring ways to make fundamental changes in the governance and management of resources, and of society-environment relationships more generally. In some cases, resilience is the preferred goal; in others, transformation may be the better option.

Recent warnings that the Colorado River may be even more short of water in coming decades than had previously been thought have prompted the most significant effort in the history of the Law of the River to bring water management structures and practices more closely into alignment with projections of future climatic conditions. Beyond the confines of the river, its tributaries, and its delivery infrastructure, however, lies perhaps the most intractable problem: population growth and related growth in water demand.

While our coupled systems have some built-in "wiggle room" for adjusting to changes in the amount and quality of available water, they remain vulnerable to serious stresses generated by the combined forces of severe extended drought and escalation in water demand. The situation calls for taking a serious look at investing in transformation.

continued on page 68

continued

For example, the “carrots and sticks” that support water-intensive practices might be changed to ones that conserve large amounts of water, such as water harvesting and permaculture, and that integrate effluent fully into potable water supplies. Such decisions constitute an investment not only in transforming the landscapes of individual property owners, but also the coupled systems of the area.

More broadly, maintaining the resilience of coupled societal-environmental systems becomes ever more problematical as the combined and escalating pressures of drought recurrence and higher temperatures – and thus higher evaporation rates – affect more and more people. Options exist today to foster resilience, but all have costs as well as benefits. As one chapter in this section observes, thinning trees in overgrown forests may help increase water availability for a few years, but may also lead to increases in erosion and sedimentation of streams.

Most proposals to stabilize and ultimately reduce emissions of carbon dioxide and other greenhouse gases into the atmosphere involve large systemic changes in human policies and practices, and thus portend major social and ecological transformation. Maximizing the benefits of such changes, while minimizing adverse impacts on vulnerable components of a system, requires crafting policies that are sensitive to local and regional contexts. For example, in a general sense managing forests to increase carbon sequestration may have beneficial payoffs in areas having vast tracts of forest. However, in the Southwest, this strategy is unlikely to contribute much toward reducing atmospheric carbon dioxide because the region lacks sufficiently large expanses of timber. As the article in this section on alternative energy sources indicates, a larger impact would be made, for example, by reducing greenhouse gas emissions generated by autos and other forms of transportation, shifting to electricity production technologies that do not require burning fossil fuels, and improving the energy efficiency of buildings.

One of the most encouraging developments today is the growing political commitment to addressing global warming issues at state and local levels across the region and escalating interest among individuals in “doing their part.” While California remains the regional leader in addressing global warming, leaders in Arizona and New Mexico have begun developing initiatives that are grounded in the environmental and social contexts of their own states.

These initiatives establish the groundwork for how resilience and transformation decisions will unfold. Information and insights such as those provided in this book illustrate the depth and breadth of the issues that must be confronted in these decision processes. They also point the way toward workable solutions that can help build resilience in those systems that must be preserved and at the same time set the stage for transformation of those systems whose time has passed.

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Population growth, warming, and water supply

Water for the ongoing influx of people in the Southwest will come at a cost

By Melanie Lenart

Expanding cities and warming climate merge dramatically in the Southwest to boost water demand. The combined effect of rising population, temperature and water use, meanwhile, threatens to take a toll on quality of life.

"We have put ourselves on a trajectory to make this a hotter, drier place," keynote speaker Grady Gammage cautioned during a June workshop in Phoenix, called "Providing water to Arizona's growing population: How will we meet the obligation?" A lawyer, Gammage helped secure regional water supplies by serving on the Central Arizona Project (CAP) board of directors for 12 years before taking his current post at the Arizona State University's (ASU) Morrison Institute.

While many workshop speakers expressed confidence that Arizona could find water to support the ongoing influx of people, their words supported Gammage's premise that residents would pay a price for continued population growth.

Higher water bills clearly will be coming down the pipeline in many cities, with current as well as future residents anteing up. Declining water quality could represent another cost as water managers consider saltier sources.

Shrinking rivers also follow rising water demand, as acknowledged by speakers at the June workshop, organized by The University of Arizona's Water Resources Research Center, and at an August event in Tucson. Another cost of the growing population and the water policy it will inspire will be measured in degrees.

Temperatures had already reached 110 degrees on the morning of the first day of the workshop, as the sun was reaching its annual peak in intensity on the summer solstice. Unrestrained population growth will make Arizona cities hotter for several reasons, Gammage suggested, naming more xeriscaping, agricultural water buy-outs, and city infill.

Xeriscaping—using desert vegetation in landscaping—uses less water, but it also does less to cool residential areas than lush grass and trees. Shifting agricultural allotments permanently to cities will reduce the region's ability to weather drought years by temporarily turning off the supply to agriculture. This increases the chances for urban water use restrictions. Promoting the infill of population within city centers saves on pipelines and other infrastructure, but makes cities even hotter as heat-trapping concrete replaces cooler open spaces.

The "urban heat island effect"—a result of concrete, buildings, and asphalt covering open land—worsens as cities become more densely populated. For instance, temperatures in Tempe (near Phoenix) increased by about 10 degrees Fahrenheit over the last century, ASU researchers have found, with about two-thirds of the difference related to the urban heat island effect and the remainder linked to global warming. The population of metropolitan Phoenix roughly doubled in three decades to top 1.4 million in 2005.

Residents who bought homes in 2005 in Arizona's central area—Maricopa, Pinal and Pima counties—can expect the surrounding population to nearly double again by the time they pay off a conventional mortgage in 2035. Their roughly 9.6 million neighbors in the merging three-county urban sprawl will contribute to a projected near doubling of water demand during that same time frame, as described in a discussion paper drafted for the workshop.

The central Arizona region can support only about 8.5 million people with the water considered "currently secured," according to the paper's preliminary analysis led by ASU researcher Jim Holway, a former assistant director with the Arizona Department of Water Resources. Beyond that population level, projected for about 2020, the supply would depend on securing additional sources such as agricultural water and wastewater effluent (Figure 1).

Additional water sources are "likely" to become available, including from the Colorado River allocations to agriculture, but are not secured at this point. Water managers are pursuing the prospect of treating wastewater effluent, among other sources, to keep up with the growing demand for potable water (For more information: http://sustainability.asu.edu/gios/waterworkshop.htm).

Projections for global warming, meanwhile, indicate regional temperatures could continue to rise throughout the century by perhaps a degree Fahrenheit a decade. That's the rate already registering in Arizona since about the mid-1970s, based on data from the Western Regional Climate Center. It's several times faster than the average rate for the world as a whole.

Higher temperatures boost water demand, especially in summer when residents run evaporative swamp coolers and water wilting plants. An average household in Tucson, for example, uses a third more water during the warm months of May through October than in cooler months.

Global warming causes other regional climate changes as well. Along with temperatures, it increases evaporation rates, rainfall variability and the risk of heat waves and drought.

continued on page 70

Water supply, continued

"We're going to have to prepare for more intense droughts than we've had in the past," acknowledged Steve Olson, executive director of the Arizona Municipal Water Users Association that covers metropolitan Phoenix. By one climate change assessment that models a slight drop in Colorado Basin precipitation along with an ongoing temperature rise, the river could run short about a quarter of the time in the coming century (*Climatic Change*, March 2004).

"I think the climate is going to change. We need to be able to react to what that change might be." Tucson Water Director David Modeer said.

Modeer and other water managers for Tucson have been alerting residents to the potential need to start converting wastewater effluent into drinking water within the next decade. Pima County residents must decide in the next few years whether to accept what some critics characterize as a "toilet to tap" plan.

It may be a tough sell. Tucson residents twice voted against even allowing Colorado River water directly into their drinking water, citing water quality issues. Residents finally agreed in 2000 to accept a blend of CAP water with groundwater. The Tucson Water Plan indicates they'll soon be asked to consider a saltier blend, with a greater share of Colorado water.

Tucson renewable groundwater could sustainably support a population of roughly 375,000—less than half the current population of the city's metropolitan area. In theory, Tucson's allotment of Colorado water could supply another 1 million people at current use rates. That would assume that drought doesn't limit the supply, and the city retains its entire share for residential use.

Currently, about 70 percent of Arizona's water, and 80 percent of its Colorado River allocations, goes to support agriculture on private and tribal lands.

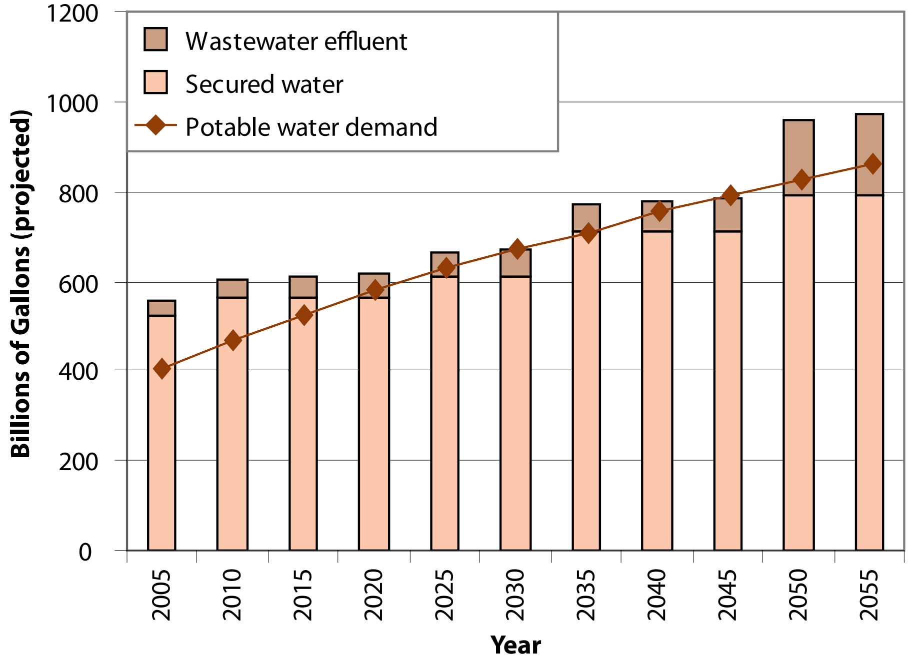

Figure 1. The population of central Arizona is projected to exceed the "secured supply" of renewable water by about 2020 given current population growth. Water managers are pursuing the prospect of treating wastewater effluent, among other sources, to keep up with the growing demand for potable water.

"Ultimately, urban and rural Arizona are competing for the same water supplies," Gammage told the group, some of who needed no reminding.

"We're a target and we know it," said Roger Gingrich, Yuma's water resources coordinator. He noted that Yuma lettuce growers supply the country, helping Arizona's third largest metropolitan area earn $1 billion a year from crops. The resources, including water, supporting this industry would not be given away lightly, he indicated.

"It's more, what are you willing to pay? When it comes to water, you'll be paying a lot," he said. Noting that bottled water sells in stores for more than $1 a gallon, he tallied the price for an acre-foot of water at about $365,000. Gingrich was speaking mostly with tongue in cheek, but he said he was serious in conveying that farmers would not sell water at the going rate. Currently, Tucson residents pay about $15 for their first 11,200 gallons of water a month. At this rate, water costs about $450 an acre-foot.

Arizona residents would pay an estimated $3,000 an acre-foot for desalinated water in a plan proposed by CAP Deputy General Manager Larry Dozier. The desalination approach he outlined would boost an average water bill to $150 to $200 a month, he said.

It would involve erecting a desalination plant and an electrical plant to power it on the Gulf of California in Mexico, given the approval of Mexico's burgeoning tourism industry on the gulf. The desalinated ocean water could help cover the million acre-feet of Colorado River water promised to Mexico, Dozier said, freeing up more of the river's share for Arizona.

Arizona's share of the Colorado could then support future development. Under current law, developments can go up in Arizona even where water supplies are deemed "inadequate" to supply homes for the century or more they may exist. Also, landowners currently can withdraw unlimited quantities of

continued on page 71

Water supply, continued

groundwater from below their land, with some caveats, even if doing so dries up nearby rivers and neighbors' wells.

In a day of interactive sessions during the June workshop, people suggested policy makers should consider the property rights of existing residents before permitting new developments. Participants also stressed the need to protect rivers when evaluating the potential impacts of new developments.

Southwestern rivers that once flowed year-round have been reduced to intermittent streams in areas where growing populations increasingly tap into groundwater or surface flows, such as Tucson's Santa Cruz River.

Even the San Pedro River has been faltering in recent years, with population growth in Sierra Vista and Benson as well as drought reducing stream flow. About seven miles northeast of Sierra Vista, the San Pedro dried up for 12 days in the summer of 2005—for the first time at least since continuous monitoring began there in 1930. It almost repeated its disappearing act in late June, but reaped the benefits of an early start to the monsoon season.

The impact on the San Pedro from water withdrawals depends in part on where wells go, explained hydrologist John Hoffman of the U.S. Geological Survey. To illustrate, Hoffman showed a map of the San Pedro River where it flowed through Arizona northeast of the Huachuca Mountains and explained the modeled impacts of 50 years of pumping 33 millions of groundwater—an amount that would support less than a thousand people a year at current use rates.

Wells located around the river near Fort Huachuca's eastern edge would draw about 95 percent of their supply from water that would otherwise feed the San Pedro River, Hoffman's preliminary map indicated. In contrast, wells located west of the river near the Huachuca's southern boundary would draw only about 30 percent of their supply from water that would otherwise go to the stream.

The area's newest spate of wells are going in exactly where Hoffman's analysis shows they would do the most damage, pointed out Patrick Graham of The Nature Conservancy, alluding to some of the development occurring in the budding towns of Hereford and Palominas right along the river.

"Groundwater supports those rivers. While there's not a legal recognition, it's a fact," Graham said. Many states, including Arizona, fail to consider the impact groundwater withdrawals have on nearby rivers, as Robert Glennon describes at length in his book W*ater Follies: Groundwater Pumping and the Fate of America's Fresh Waters*.

Graham compared groundwater basins to bathtubs, noting that rivers flow only when the basins are full enough to overflow into channels. Yet surface waters serve millions of birds as "nature's highways, hospitals, hotels, and restaurants," he said. Conservationists consider the San Pedro especially crucial as an oasis for migratory birds, as it encompasses the northern limits for some tropical species and the southern edge for some species traveling from cooler climates.

Tourism and recreation also thrive due to surface water, such as the inner tubing industry on Phoenix's Salt River.

Concern for rivers and their functions drew a crowd of about 250 people to an August talk in Tucson by Jackie King. A researcher from South Africa, King assesses ecological, social, and economic values of river systems around the world and how they change with development.

Noting that Arizona policy encourages population growth, she outlined how

continued on page 72

A natural source of water

By Melanie Lenart

Homeowners can turn their yards into oases by capturing rainwater and recycling household water, explained Brad Lancaster, author of *Rainwater Harvesting for Drylands*.

He describes harvesting principles that allow plants to thrive and thus cool the area around homes, a form of climate control that becomes more crucial with temperatures rising and populations growing.

"We're truly desertifying our so-called desert," Lancaster said during a talk this year at The University of Arizona's Water Resources Research Center. "Here's where the rivers are today," he added, showing a slide of a Tucson street flooded by monsoon rains.

Paved streets, concretized river banks, and hard bare soil all channel water away before it can soak into the ground—sometimes whisking it out of town even before it can recharge groundwater aquifers, he noted.

A permaculturist based in Tucson, Lancaster learned some of his techniques in Zimbabwe, which has a semi-arid climate similar to that in the Southwest. There, a man he calls Mr. Phiri taught him how to "plant water before planting trees" and other lessons. These include:

- Start by observing your landscape during rains, noticing how water moves and collects. Then revise after noticing what does and doesn't work.
- Start at the top of your "watershed," which on a residential lot may be a roof. Capture and/or

continued on page 72

Water supply, continued

researchers could assess some of the benefits and costs of proposed water withdrawals to encourage more informed policy decisions (*River Research and Applications*, Fall 2003).

Using extensive data on historical, present-day, and future river flow patterns and location of riparian plants, researchers could project how proposed withdrawals might impact water quality, wildlife, and tourism, for example.

"If you take half your diet away, you will change. If you take half the river water away, it will change," King told the crowd gathered at The University of Arizona. Later she reminded, "Good quality of life doesn't just mean a nice house and food in the fridge."

King noted that her approach includes working with various interest groups and individuals. With her recommended approach, scientists restrict their role to evaluating and presenting data, leaving policy decisions to the governments and stakeholders involved.

In the concluding remarks at the June conference, Kathy Jacobs encouraged water managers and the research community to explain the impact of decisions so policy makers could avoid working "in a vacuum." A onetime water manager, Jacobs now directs the tri-university Arizona Water Institute.

Water managers need to create a better link between water availability and population growth management, Gammage suggested, adding, "I don't think water managers can continue the attitude of 'We're the plumbers. You tell us what we need to do and we'll do it.' "

Melanie Lenart is a postdoctoral research associate with the Climate Assessment for the Southwest (CLIMAS). The SWCO feature article archive can be accessed at the following link: http://www.ispe.arizona.edu/climas/forecasts/swarticles.html

Natural source, continued

direct gutter water toward plants or into a storage tank.

- Start small. Use simple strategies that slow and spread the flow of water across the land, giving it time to seep down into soil.

- Maximize ground cover, especially living ground cover. Plants and mulch help soils quickly soak up water, so it won't be available for mosquito breeding.

"If nothing else, raise your pathways and patios and sink your planting areas," Lancaster suggested. That way plants will receive some of the water running off the impermeable surfaces.

Figure 2. Brad Lancaster in front of the cistern that stores rainwater in his yard. Photo credit: Melanie Lenart

During an early September tour of his yard, he pointed out a 1,200 gallon cistern—now full—that stores water channeled from his roof (Figure 2). A spigot on the side yields some of its contents with a turn of the faucet. A driveway and a strategically sliced curb pull in some of the street's flow during monsoon rains, where native plants benefit from the spillover. Corrugated zinc on the roof of his workshop drains water in rivulets into an area sprouting orange and fig trees.

The thriving saplings also receive water every time Lancaster washes a load of clothes. Recycled water draining from showers, washing machines, and other household pipes is known as greywater.

Arizona has begun encouraging residents to use greywater for landscaping, as long as they avoid draining from kitchen sinks or, of course, toilets. In 2007, the state will start providing up to $1,000 in tax credits per household to help reimburse residents who set up greywater-harvesting systems.

When employing greywater, Lancaster recommends using liquid detergents rather than powders, which use salt as filler. Also, unlike rainwater, greywater should not be stored in a tank. Lancaster encourages people to deposit it directly into mulched and vegetated soil.

Water harvesting can make a crucial difference when living in any desert. Lancaster's mentor, Mr. Phiri, became a role model for his village in Zimbabwe after turning a barren wasteland into a productive farm over the years.

"There are other people in his village literally dying of thirst in drought years, and he is raising fish," Lancaster said. "And they could be doing the same."

More information about the tax credit program, suitable detergents for greywater systems, and Lancaster's book can be found at his website: http://www.harvestingrainwater.com.

Plan to thin trees in Apache-Sitgreaves forest could increase streamflow in short term

By Melanie Lenart

As the Apache-Sitgreaves National Forest launches its stewardship project to thin about 15,000 acres of Ponderosa pine forest a year over the next decade, the question arises: Will the reduction of trees in these forests mean an increase in streamflow for the communities that border them?

The consensus of researchers who have tackled this issue is a qualified "yes." Thinning some of the trees in these admittedly dense stands of pines should lead to an increase in runoff for the streams that flow through the thinned areas—but only for a few years, and perhaps only noticeably so during years of high precipitation.

"I can't see any reason why it wouldn't have the benefit of providing additional water," University of Arizona Natural Resources Professor Peter Ffolliott said of the planned Apache-Sitgreaves thinning project. "The question is does that (benefit) persist, and of course it doesn't because the site recovers after awhile."

Typically, the increase in streamflow, a.k.a. water yield, that a thinning project promotes drops off after about five years, he noted. But if the thinning project stretches across 10 years, as planned for the stewardship project, the increase in water yield could continue for more than a dozen years, albeit it with the benefits turning up in different streams within the White Mountains watershed.

The forest stands targeted for thinning as part of the stewardship project drain variously into three major rivers: the Little Colorado, the Gila, and the Salt rivers, noted Robert Dyson, who handles public affairs for the Apache-Sitgreaves National Forest. Some of the local tributaries that stand to benefit in the near future include San Francisco, Mineral, Show Low, Silver, and Chevelon creeks.

A research project on the White Mountains' Thomas Creek headed by one of Ffolliott's then-graduate students, Gerald Gottfried, found that streamflow increased measurably in the eight years following a 1978–79 tree harvest that reduced the ground coverage of trees by about a third.

Gottfried, who now works as a research forester for the Rocky Mountain Research Station, used streamflow measurements to estimate an average increase in annual runoff of about 1 to 1½ inches based on measurements from when the logging ended in 1979 to when the study ended in 1986 (Figure 1). Runoff is the amount of water that makes it to streams after trees and soils get their fill. Like precipitation, runoff is a point measurement often reported in inches.

The water yield increase came mainly from winter precipitation (Oct. 1 through May 30 in his analysis), especially from March through May, Gottfried indicated. Apparently snow piled up in cleared openings, thus leaving less surface area susceptible to evaporative processes. However, the difference was driven mainly by wet years, he noted. Annual precipitation on the Thomas Creek watershed averaged about 30

continued on page 74

Salt cedar: Villain or scapegoat when it comes to water use?

By Melanie Lenart

Salt cedar's reputation as a high water user has made it the bane of water agencies for many decades. When the drought slowed the flow of many southwestern rivers down to a trickle in 2002, its presence along New Mexican waterways even made it a target of then-gubernatorial candidate Bill Richardson.

Upon his election, Richardson followed through with his plan to eradicate salt cedar stands lining the state's riverbeds. In 2003, the state spent $4 million to spray the herbicide Arsenal from helicopters onto stands of salt cedar, also known as tamarisk because of its scientific name *(Tamarix* species, mainly *ramosissima).* About 25,000 acres of salt cedar had been so treated by spring of this year, according to an April 1 op-ed piece in the *Albuquerque Journal* by Assistant Secretary of the Interior Rebecca Watson, who touted the eradication effort as an outstanding example of water conservation in the West.

Yet there are some who consider salt cedar to be a scapegoat. One of these skeptics is Edward Glenn, a senior research scientist with the University of Arizona's Environmental Research Laboratory. Glenn mentored then-graduate student Pam Nagler in research estimating water use of salt cedar compared to other species based on their leaf area indices and other remotely sensed data for a roughly 200-mile stretch of the Lower Colorado River.

"Particularly, salt cedar doesn't seem to be the big hog, the biggest water user, that people have given it credit for," Glenn said. "For years and years, people

continued on page 75

Runoff, continued

inches a year between 1964 and 1986, but ranged from about 20 to 44 inches.

"In high-precipitation years, it seemed there was more water in the ground than the trees could use, but this would not work in a dry year," he explained during a recent telephone conversation. "In the middle of drought—and this is not just in Arizona but throughout the U.S.—you're not going to create more water."

David Goodrich, a hydraulic engineer with the U.S. Department of Agriculture Research Service unit, concurred. Measurable water yield increases are difficult to detect in dry years or dry areas, he said, noting that a research project he worked on that involved removing woody vegetation on 10 acres near Tombstone found no difference in water yield after the treatment. The research site receives an average of about 13.8 inches in annual precipitation.

"The conclusion was that the variability or some of the uncertainty in rainfall was enough to mask the potential change in water yield," Goodrich explained.

In the case of the Apache-Sitgreaves stewardship project, any water yield increases would be seen as a fringe benefit to the main intention: to reduce fire risk in the forest stands near communities, which foresters call the wildland-urban interface.

Another potential fringe benefit, although more speculative, might be increased resistance to bark beetle outbreaks among the remaining trees in the stand. Drought stress makes it more difficult for trees to repel these invasive insects with their sap, so the thinking goes that reducing the competition for water among trees can only help boost a stand's resistance to bark beetle.

For that matter, the millions of trees killed in recent years by beetles and by fire in southwestern forests have also

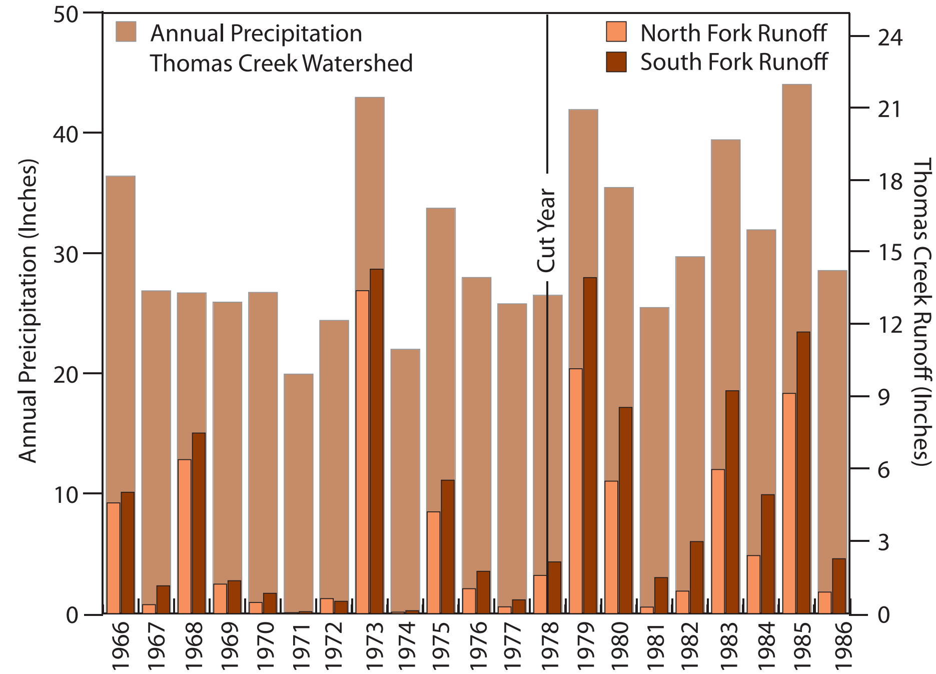

Figure 1. The South Fork of Thomas Creek in the White Mountains had a slight tendency to produce more "runoff," or water yield from overland flow, before a logging treatment that was completed on the South Fork of the watershed in 1978. After the treatment, this tendency was more pronounced, as the above graphic illustrates. However, the main difference occurred in years of high precipitation. On the graphic, the scale for precipitation for the Thomas Creek watershed is on the left, while the scale for runoff values is given on the right. Data from 1989 University of Arizona dissertation of Gerald Gottfried, School of Natural Resources.

stopped drawing water for sustenance (although their remains may still increase surface area and therefore evaporation rates). All living plants use water for tissue construction as they photosynthesize, and for nutrient transport as they transpire, with the latter describing the process of transporting water from their roots to their leaves for eventual evaporation.

It's comforting to know that there's a silver lining to the clouds of smoke and flying insects that have ravaged southwestern forests in recent years. But the increase in water yield from beetle kill and particularly from fire poses other problems—namely floods and erosion.

It's ironic that drought can actually increase the risk of floods, albeit indirectly, because it increases the risk of severe fires and insect attacks, commented Daniel Evans, a hydrologist with the U.S. Geological Survey's Tucson office. Severe fires in particular can increase flood risk by searing the soil, changing its structure so that it repels water. This, in turn, reduces the rate at which water can infiltrate soil and so increases the runoff rate, i.e. the rate at which water will flow over the land and reach streams. (For more details, see "Flooding after Fire" from the May 2003 packet at: http://www.ispe.arizona.edu/climas/forecasts/archive/may2003/may2003figs/19_Floods.html)

Like the White Mountain logging treatment, the 2003 Aspen fire on Tucson's Mount Lemmon caused peak streamflow increases when severely burned watersheds were exposed to monsoonal rains, reported Evans, who helped monitor streamflow within the Sabino Canyon and Canyon del Oro drainages. After making adjustments for precipitation differences, he estimated streamflow highs on some creeks draining the burn area were more than five times greater than they had been before the fire.

Unfortunately, the excessive streamflow turned into a wall of water that careened through the town of Oracle in August of

continued on page 75

Runoff, continued

2003, sweeping 60-year-old newspaper publisher Jim Huntington to his death.

Peak streamflow increases also occurred on watersheds draining forests affected by the Rodeo-Chediski fire. For instance, concerns over potential floods led officials to evacuate the town of Carrizo three times, Evans said. But no deaths related to fire-caused floods were reported.

The Rodeo-Chediski fire of 2002 set the Arizona record for fire severity in the past century, with about 460,000 acres burned to varying degrees. So perhaps it's not surprising that the highest measured increase in streamflow peaks occurred within that burn area, in Ffolliott's estimation.

Ffolliott was watching the televised account of the fire in action when he noticed that it was spreading to an area that he and others had worked on in the 1970s. Although they had finished the project in 1977, they had left the flume and some other measuring devices in place—and were able to relocate them within a week after the Rodeo-Chediski's devastating passage through the area.

"It was a tragic event, but it was a unique research opportunity," Ffolliott said of the fire. He and U.S. Forest Service project leader Daniel Neary used a high water mark to estimate that, at one point during monsoonal rains a few weeks after the fire, streamflow through the plume peaked at 232 feet per second —about 2,300 greater than the peak of 0.1 feet per second they measured during the 1972–77 experiment on the same creek.

The arrival of the monsoon season near the tail end of the southwestern fire season contributes to peak streamflow and erosion extremes that—along with drought—help define the semi-arid lands of the Southwest. Particularly in the case of severe fire, higher erosion rates tend to accompany the dramatic increase in streamflow peaks, with soil often seared and formerly protective vegetation shriveled or dying.

On the severely burned watershed of the Rodeo-Chediski fire, Ffolliott and Neary measured post-fire sediment yield rates of about 25 tons per acre. This is about five times higher than the baseline rates of 4 to 5 tons per acre they calculated for the 1972–77 time frame.

Similarly, Evans noted that the July Nuttall Complex wildfire on Mount Graham led to erosion that dumped at least 30 feet of sediment into the Frye Mesa Reservoir. But, as in the case of streamflow and water yield, he estimated that it generally takes about five years or less for a mountainside to stop shedding topsoil at unusually high rates.

Streamflow peaks on the creeks Ffolliott is monitoring at the Rodeo-Chediski site are already coming back to normal, at least at the larger scale of the watershed, he indicated.

"Actually, peak flow declined quite rapidly down to pre-fire conditions. I think we still have some elevated flows coming through, but it's nothing like in that first year," he said. "During our first trip out there, it was during the monsoon and thunderstorms started. You felt a little uneasy. Literally, we were the only living things out there. Now it's getting green again, which is kind of nice."

Nature has a track record of rebounding from disturbance, whether it's from fire, insect invasion or tree cutting. Assuming topsoil remains, vegetation will find a way to respond with a fresh flush of growth to the inherent productivity of a site—which is based on the input of sunshine, snow and rain. As it does, the transient benefit of increased water yield will fade away—like a far-away cloud drifting across the horizon.

Salt Cedar, continued

would quote these figures that they were using 3 to 4 meters of water a year, but they didn't have good methods for measuring it."

More recent techniques using sophisticated technology have found that salt cedar trees were using comparable amounts of water as the native cottonwood and willow trees they are seen as replacing.

"They (researchers) found that it actually uses less water than Bermuda grass. So your back lawn is actually using more water than salt cedar," Glenn said. Nagler, Glenn and others reported in a 2004 paper in *Agricultural and Forest Meteorology* that salt cedar actually appeared to consume less water than cottonwood, based on leaf area indices.

A year-long study conducted by Steve Hansen, an assistant area manager for the Albuquerque office of the U.S. Bureau of Reclamation (USBR), and colleagues found that salt cedar at the site they measured in the late 1990s used about 4 feet of water a year. This is about one third of the 4 meters it had been accused of consuming, although values would vary somewhat by site. Salt cedar used about the same amount of water as alfalfa, and roughly 20 percent more water than cottonwood, Hansen's research indicated.

Glenn credited Juliet Stromberg, an associate professor at Arizona State University, with launching the effort to examine the salt cedar issue objectively.

Stromberg explained by telephone that she falls into the camp of researchers who suspect salt cedar has proliferated because of changes in streamflow patterns, livestock grazing, water availability, and water quality. Given sufficiently high water tables and natural flood regimes (which reduce soil salinity) and protection from grazing, cottonwood

continued on page 76

Salt Cedar, continued

and willow will grow taller than salt cedar and therefore maintain dominance in stands, her research indicates.

"There is an assumption that salt cedar has contributed to changes in stream hydrology and geomorphology that has, in turn, reduced the ability of cottonwood and willow to survive," she explained.

However, seeds from both native species are distributed and nourished by a natural flood regime, which typically is lacking in the dam-regulated environment of western rivers. In addition to salt cedar, houses tend to line the rivers, and it's doubtful many residents would welcome annual floods. Also, the ongoing water use by the growing population of people and by long-time farmers may be lowering the water table beyond the tolerance of cottonwood and willow.

"If salt cedar is not the cause—if it's just sort of a symptom—then if you clear the salt cedar you haven't addressed the root cause of vegetation change," she added. Rather than native vegetation, salt cedar is likely to return, unless changes occur in the management of rivers and floodplain lands.

New Mexico planners have not yet moved fully into the stage of re-establishing native vegetation to replace the Arsenal-killed salt cedar stands. Although thousands of salt cedars lining the Middle Rio Grande River are "deader than a hammer," many of them remain standing on the landscape while officials confirm their demise, Hansen said. State officials are trying to figure out what to do with all the dead wood, which can act as a fuel source in case of fire, or transform into dangerous woody debris in case of floods. Until then, little can be done to re-establish native species, he indicated.

Streamflow in river stretches in which salt cedar was killed are not showing clear signs of an increase in water yield since eradication, said Hansen, who attributed this to an inability to measure water levels accurately enough to detect a difference. He compared the concept of measuring a difference to trying to detect how much water a person has consumed based on a change in their weight. Instead, he suggested it is more accurate to measure the actual amount of water the person consumed, as with studies like his that document how much water a salt cedar tree consumes.

Given the relatively small portion of the water allotment consumed by "phreatophytes" like salt cedar, cottonwood, and willow—which the USBR estimates at about 7 percent of its total water budget along the lower Colorado River from Hoover Dam to Mexico—it's even more understandable that a difference would be difficult to detect. Based on the 7 percent proportion, even if salt cedar represented all the phreatophytes and was completely replaced with cottonwood stands that used 20 percent less water, the best the Bureau could hope for would be about a 1.4 percent increase in total available water along this stretch.

Still, in the Middle Rio Grande, the savings estimated from the approximately 60,000 acres covered by salt cedar in 2002 potentially would amount to about 40,000 acre-feet of water, Hansen noted. However, if riverside trees follow water use patterns similar to mountaintop trees, the water yield increase may be more obvious during wet years than dry ones. (See related story in this issue.)

Also, it's a bit more complicated than a one-to-one replacement of salt cedar with native vegetation because cottonwood and willow trees won't necessarily be able to survive in the same places occupied by salt cedar, noted Fred Nibling, a research botanist for the USBR's Denver office.

"The difference is the footprint on the terrain that salt cedar is capable of occupying is much greater than that of cottonwood and willow," he elaborated. So the eradication program could help the USBR in its mission to deliver the allotted water to its clientele, which includes farmers near New Mexico's Elephant Butte Reservoir who have not received their full allotment for several years.

U.S. Bureau of Reclamation scientists work on methods for revegetation that can be used once they eradicate the salt cedar lining the banks of Pecos River near Carlsbad, New Mexico. Although most salt cedar eradication efforts in New Mexico involve using chemical control, the area above is about five miles from a Pecos River site where scientists are trying biological control by introducing a beetle that kills salt cedar. Photo by Fred Nibling.

Salt cedar is considered an invasive species by most ecologists. It was introduced to the West from Asia, in part to help control erosion. Its ability to live along relatively dry channels that do not support other riparian species does help prevent erosion, but salt cedar is also accused of making the soil more saline via leaffall, and of contributing to flood risk by narrowing channels.

Nibling acknowledged that the situation posed an environmental challenge, with the goal of controlling invasive plants (salt cedar) competing with the goal to protect endangered species (including the willow flycatcher, which does well in salt cedar stands).

"It's an interesting quandary," Nibling said. "It's really a challenge to our scientific skills to make it work for both groups."

Melanie Lenart is a postdoctoral research associate with the Climate Assessment for the Southwest.

Global warming inspires a look at solar, wind energy

Southwest eyeing ways to cut emissions from fossil fuels such as oil and coal

By Melanie Lenart

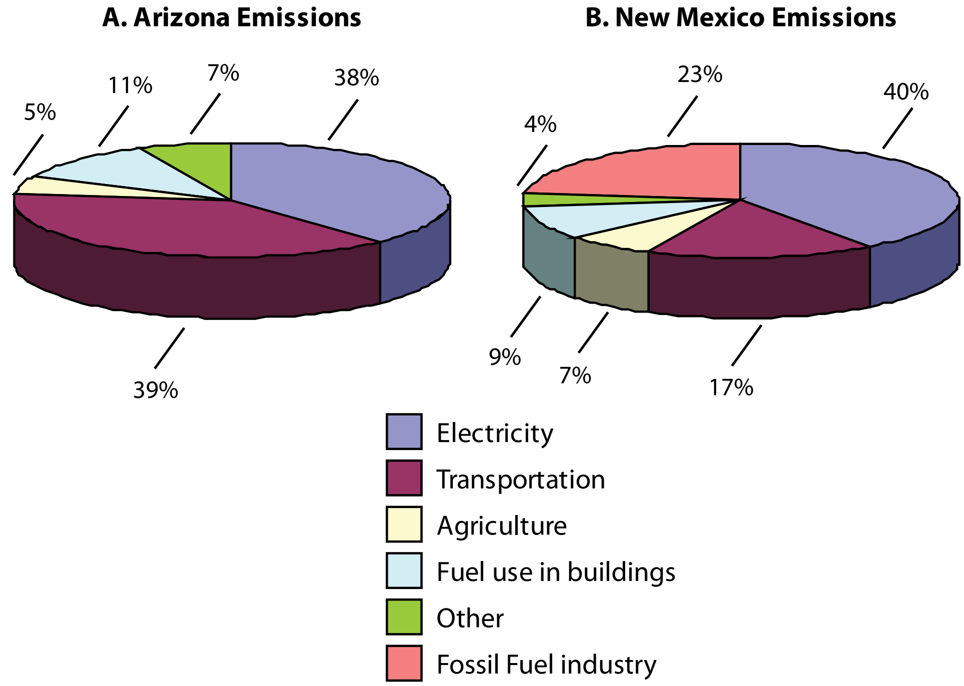

Figure 1. The pie charts show the source of greenhouse gas emissions in Arizona (a) and New Mexico (b) based on 2000 data. New Mexico has an additional category, Fossil Fuel Industry, which largely reflects its coal mining and processing operations.

Now that many Americans accept the reality of global warming, they want to do something about it. In the Southwest, that desire is being harnessed into initiatives to improve energy efficiency and boost alternative forms of power, such as solar and wind energy.

The rising temperatures of recent decades trace back largely to emissions of greenhouse gases, mainly from the burning of fossil fuels like coal, gas, and oil. So the first step toward reigning in global warming involves reducing fossil fuel emissions.

The United States releases more greenhouse gases from fossil fuels than any other nation. Per-person emissions tally about six times higher in the United States than in China, the runner-up for title of world's biggest producer of greenhouse gases. Yet the U.S. government has declined to join the international effort to reduce greenhouse gas emissions, known as the Kyoto Protocol.

Many states, cities, companies, and individuals are attempting to fill the void left by the federal government. New Mexico and Arizona are making efforts to reduce fossil fuel emissions by supporting alternative fuels and improving energy efficiency. The state efforts also affect cities, companies, and individuals, especially those interested in powering their homes and offices with solar energy.

Statewide initiatives

"The governors are moving on this primarily because the federal government is not," explained Sandra Ely, New Mexico's Energy and Environment Coordinator. Ely served as the point person for the state's Climate Change Advisory Group, which released an action report in December. Arizona released its action report in mid-2006. The groups identified major sources of greenhouse gases (Figure 1) and recommended ways to reduce them. (See links to these documents on page 6.)

In September, Arizona Governor Janet Napolitano responded to the report by issuing an executive order requiring the state to drop back to 2000 levels by 2020, and to 50 percent below 2000 levels by 2040. At the time, she noted that the proposed recommendations would actually save money, amounting to $5.5 billion through 2020 and more in subsequent years.

In New Mexico, Governor Bill Richardson had issued an executive order in 2005 setting up the advisory group and asking it to think of ways to reduce the state's total greenhouse gas emissions to 2000 levels by the year 2012, to 10 percent below those levels by 2020 and to 75 percent below by 2050. To address the quotas, the advisory group decided to focus on the electricity consumed within the state, which represents roughly a quarter of the all the greenhouse gas emissions produced. The governor followed up with an order last month prescribing some actions, including making new buildings and cars more energy-efficient.

Both states face the challenge of trying to stabilize greenhouse gas emissions even as their populations explode. The number of Arizona residents rose by 40 percent during the 1990s, while New Mexico's population increased by 20 percent. Population growth averaged 13 percent in the nation during this time frame.

Arizona's population growth is translating directly into the country's highest growth rates in greenhouse gas emissions, noted Kurt Maurer, an Arizona Department of Environmental Quality employee who helped organize Arizona's Climate Change Advisory Group.

continued on page 78

Sun and wind, continued

"Our growth rate is outpacing astronomically what other states are experiencing. We're the fastest growing state in the country," Maurer said.

In both states and the country as a whole, per-capita greenhouse gas emissions—measured in metric tons of carbon dioxide equivalent per person—remained roughly stable since 1990.

New Mexico's large coal industry coupled with its relatively small population help make the state's per-capita greenhouse gas emissions about double the national average. The New Mexico advisory group targeted changes in this sector as one of the most effective ways to reduce overall emissions.

Arizona falls below the national average for greenhouse gas emissions per person, in part because the region's mild winters demand less heating. Still, electricity demands for Arizona homes have quadrupled in recent years as developers build larger structures and air conditioners replace swamp coolers.

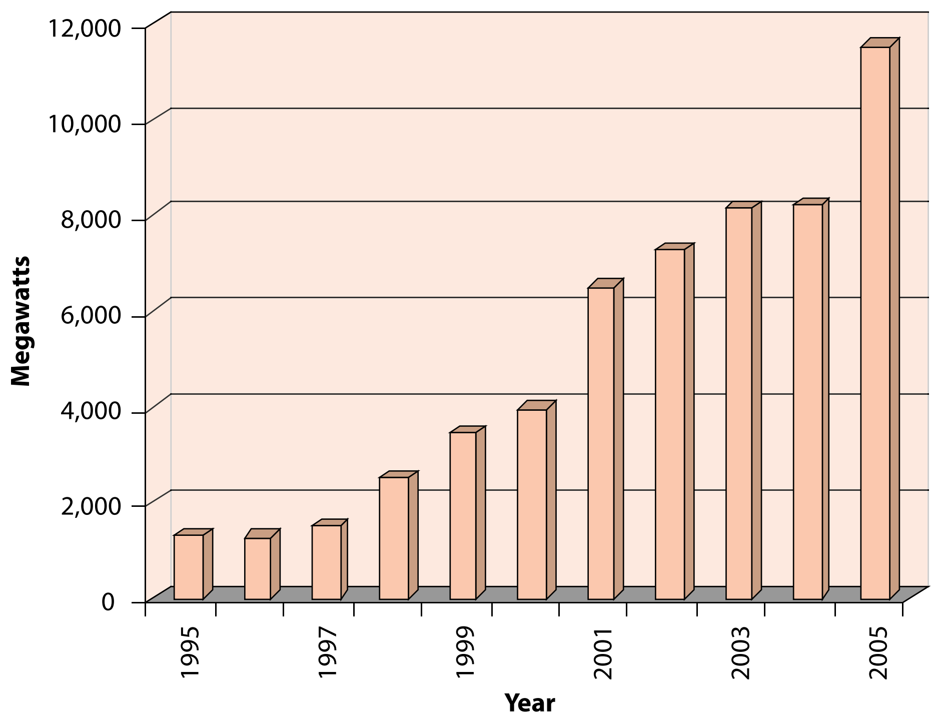

Figure 2. Wind power installments, measured by the capacity of windmills set up each year, rose by an average of 24 percent a year since 2000. Data from the Global Wind Energy Council.

Better buildings

Energy use in buildings accounts for about two-fifths of greenhouse gas emissions in the Southwest, counting the lighting and cooling provided by electricity. This has inspired leaders in both states to push for more energy-efficient structures.

Governor Richardson has promised to move forward on several regulatory fronts that don't need legislative approval. These include requiring contractors to follow the green building rating standards known as LEED, for Leadership in Energy and Environmental Design. This energy-efficient approach offers one of the best economic returns, Ely said.

"You may have some initial upfront costs of maybe 2 percent more, but you get so much back from that initial investment that you make the money back fairly quickly," she noted. Although homeowners will pay a bit extra for the home, the longer-term energy savings would amount to about $12 per ton of carbon dioxide equivalent by 2020, the report projects.

Even existing homes sometimes can benefit from improvements in energy efficiency, noted Tom Goldtooth, executive director of the Indigenous Environmental Network. Some reservation homes even have ice building up in corners, a sign that energy is leaking out of the cracks, he explained during a December Tribal Lands Climate Conference held in Yuma.

Federal tax credits for home improvements including insulation continue through this year. (See links on page 6.)

Fuel-efficient cars

Greenhouse gas emissions from vehicles rival the amount coming from energizing buildings in Arizona. Transportation accounts for about 39 percent of fossil fuel emissions in Arizona and 17 percent in New Mexico. Our nation's driving habits account for about half of the auto emissions around the planet, a 2006 Environmental Defense study showed, in part because Americans favor large vehicles with low gas mileage.

New Mexico plans to shift into more stringent vehicle emission standards by adopting California's Clean Car guidelines. California's interest in reducing its greenhouse gas emissions and related air pollution inspired Fran Pavley and other legislators to set a quota for electrical cars and restrict the sale of vehicles with low fuel efficiency. Auto makers and their organizations have sued to keep the state from implementing the law.

Arizona is holding off on adopting the California standards until the lawsuit is settled, Maurer said. In the meantime, the governor issued an executive order requiring that departments purchase

continued on page 79

Sun and wind, continued

fuel-efficient or hybrid vehicles so that the official fleet will meet these standards by 2010.

Plans are also moving forward for Arizona Grain, Inc., to open an ethanol production plant in Maricopa by mid-year. The company plans to convert corn into 50 million gallons a year of a fuel blend containing 85 percent ethanol. Ethanol is an alternative to oil that emits fewer pollutants than a conventional system, including perhaps 20 percent fewer greenhouse gases.

However, some policy experts worry that its widespread adoption could worsen conditions for the world's poor in the long run. Lester Brown, president of the Earth Policy Institute, has cautioned that a large-scale move to ethanol would force less developed countries to compete with wealthy countries for world grain supplies. Because of this risk, Brown instead promotes developing wind energy to power electric vehicles.

Wind power

Whether cars reap the bounty of wind energy in the Southwest or not, utilities in both states will be employing more windmills to meet requirements that renewable energy comprise a greater share of their generating capacity. Existing laws require Arizona to meet 15 percent of its electrical needs from renewable sources by 2025, while New Mexico must obtain 10 percent by 2011.

New Mexico already has a 204-megawatt wind farm in House, with windmills dotting the landscape on private ranches amid grazing cattle, Ely pointed out.

"The ranchers love it. It's a great utilization of their ranchland," she added. The leases for windmills provide an ongoing source of income to ranchers with a livelihood that is subject to change with climate fluctuations.

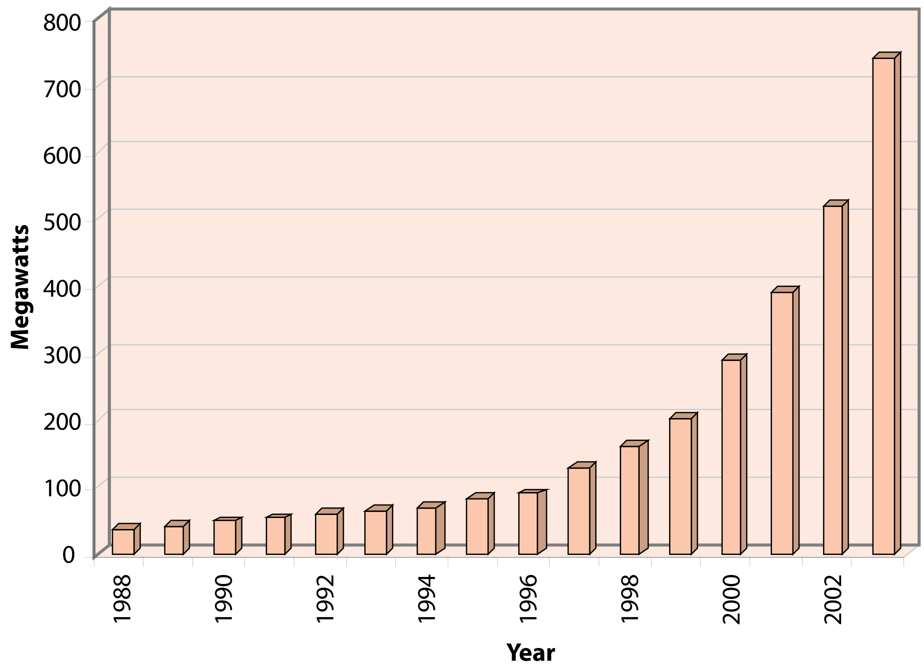

Figure 3. Electrical generation from solar cells lags behind wind globally, but the rate of increase surpasses 30 percent a year since 2000. Data here are estimates based on published graphs of information from PV Energy Systems, Inc.

According to Ben Luce, director of the New Mexico Coalition for Clean and Affordable Energy, New Mexico will need more electricity transmission lines to profit from wind potential. The coalition supports adding transmission lines throughout eastern New Mexico, a windy area that could eventually supply 4,000 to 8,000 megawatts of wind power—enough to power the whole state, he said

"A lot could change in this whole discussion in the next couple of years if we get this off the ground. Basically we could displace coal in the Southwest," Luce ventured. "The beauty is this is all local technology, so it won't hurt the economy. It could even help it."

New Mexico could develop a wind turbine manufacturing plant in an Albuquerque railyard under one proposal on the table, Luce said. Discussions call for the plant to produce windmills that can generate between 1.5 megawatts and 4 megawatts of electrical power each.

A shortage of windmills threatens to derail some U.S. projects in the short term. Many experts consider the shortage temporary, soon to be relieved with upcoming windmill production plans.

China currently overwhelms the windmill market with its demand, but lately the nation of 1.3 billion people has been stepping up its own production of windmills in hopes of meeting its needs independently. An upswing in windmill production in China and other countries is expected to ease the shortage within a few years.

At 10 cents a kilowatt-hour and falling, wind energy prices compete directly with electricity produced from fossil fuels. This helps explain their growing popularity around the world (Figure 2). Creating solar-powered electricity, meanwhile, remains relatively expensive, although passive solar heating of water pays off quickly. As a result, solar electrical systems haven't been keeping pace with wind except in rates of increase (Figure 3).

continued on page 80

Sun and wind, continued

Solar power
Both Arizona and New Mexico provide cash incentives to homeowners to supplement federal subsidies for renewable energy. As a result, the government covers about half the cost of rooftop panels using photovoltaic cells (PVCs). (See links to the right.)

A roof-mounted system from American Solar, which participated in Arizona's climate change advisory group, would cost about $14,000 after cashing in federal and state credits, explained spokesman Tom Alston. A system this size would supply half the electrical needs of a typical Arizona home, he said.

American Solar's systems run about $3 per watt of electrical energy installed, or $3,000 per kilowatt, Alston estimated. Electric bills come in kilowatt-hours, which measures the number of hours in which a system uses 1,000 watts of energy. Although solar energy is produced only while the sun is shining, Southwestern homeowners generally can sell their extra electricity to their utility companies at retail prices, then buy back what they need during the night.

The investment pays off before the 25-year warranty runs out, Alston said, noting it would yield a 6 and a half percent return over its lifetime assuming a modest increase of about 3 percent a year in electricity rates.

"But it's also like buying an energy future," Alston added, referring to the stock market tactic of banking on the likelihood of future price increases. "Every time the rates go up, the system becomes more valuable. I'm essentially ensuring my rates don't go up for the next 25 years."

Arizona Public Service has one of the world's largest electrical plants using solar power. Its Springerville, Arizona, plant hosts a 5-megawatt facility. American Solar also is finalizing plans for a 1-megawatt solar plant on the Gila River Indian Reservation south of Phoenix.

Luce hopes to lure PVC manufacturing plants into New Mexico, especially in places like Demming and Las Cruces where they could supply viable sunny sites nearby. An Albuquerque development known as Mesa del Sol might benefit from Sandia Laboratory efforts on a version of power known as concentrated solar power, he said.

With the concentrated approach, lens arrays follow the sun's daytime passage through the sky, focusing the captured light onto PVCs, explained Roger Angel, director of The University of Arizona's Mirror Lab.The Mirror Lab is researching concentrated solar power, applying its expertise in astronomy to the effort.

"It's like many little telescopes looking at the sun," said Angel. With the focused energy, fewer PVCs can yield more electricity compared to conventional solar. Angel has a team of investigators working to refine the materials and technique in the hope of bringing costs into the commercial range. "There's no difficulty in making energy from the sun," he said. "The key issue is can you do it for $1 a watt [installed], not $4 a watt."

Creating energy from PVCs remains relatively high for several reasons. Germany's appetite for solar panels is helping to keep demand greater than supply. Also, a shortage of refined silicon, an essential material for PVCs, limits production. Concentrating solar power could help get past this barrier because it provides more energy per unit-area of PVCs.

The Southwest is leading the way on concentrated solar, as befits the region with the lion's share of the nation's harvestable sunshine. An APS project in Red Rock, Arizona, is planning to use concentrated solar power to heat oil to generate power, Alston said.

By tapping into the power of the sun and wind and improving the energy efficiency of buildings and cars, officials hope to curb the growth of greenhouse gas emissions. This, in turn, could help stabilize climate and avoid some of the impacts of the ongoing global warming.

There's still a long way to go, but government mandates are fueling a revived interest in alternative power and conservation. Those who buy into these efforts enjoy the satisfaction of knowing they're doing their share to stabilize climate.

An upcoming article will address efforts to reduce greenhouse gas levels via forest management, carbon sequestration, and renewable energy credits.

Melanie Lenart is a postdoctoral research associate with the Climate Assessment for the Southwest (CLIMAS). The SWCO feature article archive can be accessed at the following link: http://www.ispe.arizona.edu/climas/forecasts/swarticles.html

Helpful Links

Arizona Climate Change Advisory Group
http://www.azclimatechange.us/

New Mexico Climate Change Advisory Group
http://www.nmclimatechange.us/

Database of State Incentives for Renewables & Efficiency
http://www.dsireusa.org/

Energy Star on federal incentives
http://www.energystar.gov/index.cfm?c=products.pr_tax_credits#1

New Mexico Coalition for Clean & Affordable Energy
www.nmccae.org

Calculating individual greenhouse gas emissions
http://www.cool-it.us/index.php?refer=&task=carbon

Everybody counts when reigning in global warming

What businesses and individuals can do to mitigate carbon dioxode emissions

By Melanie Lenart

Imagine a drier and warmer Southwest, a region in which heat waves, droughts and, paradoxically, floods become increasingly frequent, and snow cover dwindles. These projections, made by the world's leading climate scientists, suggest that climate change will hit the Southwest harder and sooner than some other areas of the country if global warming continues unchecked.

In the face of such a dire scenario, how can the average citizen possibly help? Certainly not everybody can afford to put solar panels on their roofs to reduce their contribution to global warming, but there are many ways individuals and businesses can reduce their impacts on climate. Purchasing carbon offsets from various groups, planting trees, driving less, adjusting the thermostat, and other individual efforts collectively add up to valuable cuts in the emissions that contribute to global warming.

Energy credits

For about $20 a month, the average American can eliminate greenhouse gas emissions, according to the Cool It! campaign, a carbon offset project run by a coalition of four groups (Figure 1). It sounds almost too good to be true, considering all of the problems associated with rising industrial greenhouse gas emissions and their role in global warming. Society's current production of greenhouse gases—mainly from the burning of gas, oil, and coal—is projected to boost Southwest temperatures about 0.7 degrees Fahrenheit a decade on average throughout this century. That rise brings a host of predictable changes, such as a reduction in snow cover and an increase in heat waves, as well as the potential for troublesome climate surprises.

A carbon offset investment, which varies by individual habits, allows people to virtually erase their greenhouse gas emissions, supporters say. Critics charge that the international carbon trading system and the U.S. adaptation of it create illusions about what needs to be done to reign in global warming.

The Cool It! campaign lets people offset their carbon emissions by supporting a 66-megawatt wind farm in southern California. The campaign gives people Renewable Energy Credit certificates (RECs), also known as green tags,for the energy produced when their money brings the generated wind energy down to market value, explained Julio Magalhães of the Sierra Club, one of the groups involved in the campaign.

"You're actually paying only this tiny cost difference, which is the difference between the price of coal versus wind," he said. A penny or two per kilowatt-hour can thus go a long way, explaining why the cost is relatively low. "For the price of a café latte per week, you can offset your carbon emissions," he added. The contributions are also tax-deductible.

In another effort to cut emissions, *Native*Energy, a majority tribally-owned company, uses contributions to support renewable energy, said Robert Gough, of the Intertribal Council on Utility Policy. The carbon offsets in this case count as green tags. *Native*Energy's efforts support the construction of new tribally-owned renewable energy projects that might not be built otherwise, Gough said.

"That money is there to finance renewable energy projects. The finance piece *Native*Energy brings is a significant factor in getting that project built," Gough said. For instance, offsets purchased by *Native*Energy covered about 25 percent of the hardware cost of a 750-kilowatt wind turbine on the Rosebud Sioux Reservation in South Dakota. Now the Rosebud Sioux Tribe is working out the final details of a 30-megawatt wind farm, also with support from selling green tags, he said.

Offset projects often sell credits based on the expected life span of the project. Putting up a windmill involves taking out a loan that requires operators to maintain the system for its expected life span, typically 25 years, Gough noted.

Many southwestern utilities allow their clients to support renewable energy by adding a surcharge to their bill, which in some cases is applied toward the purchase of solar energy from other customers. The U.S. Environmental Protection Agency (EPA) lists the utilities that provide this option on its Green Power website (see links on page 5).

But not everyone supports the concept of carbon offsets. At this stage, no national accounting system guarantees a carbon offset credit is sold only once or that it delivers what it promises, said Tom Goldtooth, the executive director of Indigenous Environmental Network and coauthor of the 2006 book *Carbon Trading*.

"The elders said if there is something you can't translate, beware. How can you translate trading hot air?" he asked rhetorically during a December Tribal Lands Climate Conference held in Yuma, Arizona. Goldtooth directed his harshest criticism toward the international carbon trading market. "One of the concerns is that it provides no incentives for clean energy," he said.

Offset programs can give Americans a false sense that by writing a check, they can stop worrying about how much

continued on page 82

Reigning in global warming, continued

they drive or use air-conditioning, he indicated. "The carbon trading culture continues to feed our addiction and doesn't address the issues of consumption."

Tree-planting projects can allow companies to gain carbon offset credits for planting monocultural plantations, including some that displace indigenous communities as well as native species, Goldtooth said. Also, there's no guarantee that forests will survive the length of some credits. Just as some groups will sell credits for the expected life span of a windmill, others will tally forestry credits by assuming each tree will survive for several decades. Yet if a forest goes up in flames, some of the carbon that was presumed offset goes up in smoke. Development could also take down some tallied trees. Neither the Cool It! campaign nor *Native*Energy includes carbon offset projects that involve tree-planting.

The power of plants

Global warming adds another challenge to the fate of some forests. Temperatures—and therefore evaporation rates—are rising. Changes in precipitation patterns remain mostly unpredictable, although the Intergovernmental Panel on Climate Change (IPCC) summary released February 2 projects that dry regions in general could get drier. Trees need relatively high moisture levels to survive, so lengthy droughts or shifts in wind and rain patterns could convert some forests into grasslands and deserts.

Plants and the ocean currently absorb about half the carbon dioxide emitted by fossil fuels globally. These natural systems also absorb the carbon dioxide released by worldwide deforestation. So plants, especially trees, can help curb global warming. Plants build their tissues from water and carbon dioxide. Using energy from sunlight, they transform these raw materials into carbohydrates that they use to survive and grow.

Sources of Emissions	Annual Carbon Dioxide Emitted	Monthly Cost to Offset
 Car Travel	10,900 lbs	$9.87
 Air Travel	1,500 lbs	$1.41
 Electricity Use	6,000 lbs	$5.42
 Natural Gas Use*	2,000 lbs	$1.82
Total:	20,400 lbs	$18.52
*Values are a bit higher for propane or heating oil use		

Figure 1. The values above show what the average American contributes every year in carbon dioxide emissions from driving, flying, powering, and home heating, as tallied by the Cool It! campaign. Values do not include contributions from the manufacturing of products purchased, waste disposal, or other activities.

New Mexico forests capture about 21 million metric tons of carbon dioxide a year, while Arizona forests absorb an estimated 7 million, according to the respective states' Climate Change Advisory Group reports featured in last month's *Southwest Climate Outlook* article.

But when they burn, forests release some of that carbon dioxide. Arizona's forests, for example, released the equivalent of about 2.7 million metric tons of carbon dioxide during wildfires in 2002. (This value comes by applying IPCC and EPA conversion factors to emissions data collected by the Western Regional Air Partnership.) The estimate for how much carbon dioxide Arizona's forests absorb each year took wildfires into consideration, including the 2002 Rodeo-Chediski forest fire that burned 468,000 acres in the White Mountains.

Forest management practices can reduce the risk that a wildfire will reach into the treetops, which releases more carbon and kills more trees than a surface fire. Thinning out some of the trees can reduce the odds that a surface fire will explode into crown fires in southwestern forests, according to a study led by B.A. Strom of Northern Arizona University assessing damage from the Rodeo-Chediski fire. The wood from trees thinned out of forests can heat homes, schools, and businesses or provide electricity when burned. Forest Energy Corporation converts the thinned trees from White Mountain forests into pellets that burn clean

continued on page 83

Reigning in global warming, continued

enough to use even on smog-alert days, explained Robert Davis, president of the Show Low, Arizona-based company.

Burning plant products has less impact on modern greenhouse gas levels than burning fossil fuels because of the time frames involved. The carbon from fossil fuels was captured millions of years ago, while the carbon from plants came from modern times. As long as the forest or farm that provided the plant products remains in place, new plants can start sequestering carbon all over again.

Carbon sequestration

In the context of managing greenhouse gases, carbon sequestration includes protecting forests and reforestation projects. Carbon sequestration also involves pulling carbon dioxide out of industrial emissions before they leave the smokestack and placing them into long-term storage.

Many policy analysts consider the sequestration of smokestack carbon essential, as the world's two biggest producers of greenhouse gases—the U.S. and China—both have centuries' worth of coal reserves to power electrical plants and industry. Coal emits almost twice as much carbon dioxide as natural gas to supply an equal amount of energy. At this point, it's expensive to sequester carbon, so few companies will embrace the practice without government incentives or mandates. So far this method has been restricted to small demonstration projects, but that could change in the near future. The U.S. Department of Energy plans to build a power plant that will gasify coal and capture all the plant's emissions for storage, while British Petroleum and General Electric are working together on a California power plant that will sequester carbon for long-term storage (*Science*, February 9).

Individual acts add up

When the carbon is tallied at the end of the day, individual acts to conserve energy count. Fortunately, saving energy often means saving money.

Among the largest contributors to greenhouse gases in the United States are vehicles. U.S. vehicles generate about half of the world's greenhouse gas emissions, according to a 2006 report by the Environmental Defense Fund. Driving smaller cars or hybrids, walking or biking, living closer to work, keeping tires full, or even lumping errands together for more efficient trips can help save gas, which translates into fewer emissions.

In the Southwest, heating water with the sun alone can work with a passive solar system. In summer, even conventional water heaters can be turned off if they're located in the outdoor sun. Washing clothes in cold water and installing low-flow shower heads and water-saving toilets all contribute to valuable savings. Turning down the thermostat in the winter and turning it up in summer generates savings. Similarly, choosing a swamp cooler over an air-conditioner is more energy-friendly and economical. Landscaping also cools the local environment via the water evaporated through plant leaves. Taller species can provide shade, perhaps even reducing home cooling costs. By using a permaculture approach, homeowners can conserve energy without increasing their water bills. (*Southwest Climate Outlook,* September 2006).

Using compact fluorescent light bulbs and turning off lights that aren't in use can cut down on energy use. Unplugging appliances contributes because most electronic devices continue to draw energy even when shut down. Recycling, buying fewer products, and using second-hand products also reduce energy consumption because of the emissions generated in the manufacturing industry.

In short, there is no replacement for individual action to conserve energy and reduce greenhouse gas emissions. Emissions add up household by household, car by car—and energy savings will too. With creative innovations for sequestering carbon, a willingness to support renewable energy, recognition of the value of plants, and many small efforts by individuals, this country can begin to reign in global warming. The time to act is now, before our climate changes into something unrecognizable that will make even seasoned southwesterners wonder how to handle the heat.

Melanie Lenart is a postdoctoral research associate with the Climate Assessment for the Southwest (CLIMAS). The SWCO feature article archive can be accessed at the following link: http://www.ispe.arizona.edu/climas/forecasts/swarticles.html

Helpful Links

Green Power Locator
http://www.epa.gov/greenpower/locator/index.htm

***Native*Energy**
http://www.nativeenergy.com/

Green-e
http://www.green-e.org/

Climate Neutral
www.climateneutral.com/

Carbon Trading: A Critical Conversation on Climate Change, Privatization and Power
www.dhf.uu.se

More ideas on Taking Action
http://www.climatecrisis.net/takeaction/

Forest Energy Corporation
http://www.forestenergy.com/

Intergovernmental Panel on Climate Change summary
http://www.ipcc.ch/SPM2feb07.pdf

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